ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES®

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Guidelines for Design, Selection and Application of Conformal Coatings

Developed by the Conformal Coating Handbook Task Group (5-33c) of the Cleaning and Coating Committee (5-30) of IPC

Users of this standard are encouraged to participate in the development of future revisions.

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Acknowledgment

Any Standard involving a complex technology draws material from a vast number of sources. While the principal members of the Conformal Coating Handbook Task Group (5-33c) of the Cleaning and Coating Committee (5-30) are shown below, it is not possible to include all of those who assisted in the evolution of this standard. To each of them, the members of the IPC extend their gratitude.

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1 SCOPE

1.1 Introduction Conformal coatings are used in conjunction with printed circuit assemblies (PCAs). The designer and the users of conformal coatings for electronics applications should be aware of the properties of various types of conformal coatings and their interactions with PCAs to protect the PCAs in the end-use environment for the design-life of the PCA (or beyond). This document has been written to assist the designers and users of conformal coatings in understanding the characteristics of various coating types, as well as the factors that can modify those properties when the coatings are applied. Understanding and accounting for these materials can ensure the reliability and function of electronics.

1.2 Purpose The purpose of this handbook is to assist the individuals who either make choices regarding conformal coating or who work in coating operations. This handbook represents the compiled knowledge and experience of the IPC Conformal Coating Handbook Task Group. It is not enough to understand the properties of the various conformal coatings, the user needs to understand what is to be achieved by applying the conformal coating and how to verify that the desired results have been realized.

1.3 Scope Conformal coating, for the purpose of this document, is defined as a thin, transparent, polymeric coating that is applied to the surfaces of PCAs to provide protection from the end-use environment. Typical coating thickness ranges from 12.5 µm [0.49 mil] to 200 µm [7.9 mil].

Processing characteristics and curing mechanisms are dependent on the coating chemistries used. The desired performance characteristics of a conformal coating depend on the application and should be considered when selecting coating materials and coating processes. Users are urged to consult the suppliers for detailed technical data.

This guide enables a user to select a conformal coating based on industry experience and pertinent considerations. It is the responsibility of the user to determine the suitability, via appropriate testing, of the selected coating and application method for a particular end use application.

A conformal coating may have several functions depending on the type of application. The most common are:

- To inhibit current leakage and short circuit due to humidity and contamination from service environment.
- To inhibit corrosion.
- To improve fatigue life of solder joints to leadless packages.
- To inhibit arcing, corona and St. Elmo's Fire.
- To provide mechanical support for small parts that cannot be secured by mechanical means, to prevent damages due to mechanical shock and vibration.

1.4 Terms and Definitions

Acetone – A volatile fragrant flammable liquid ketone C_3H_6O used chiefly as a solvent and in organic synthesis.

Adhesion promotion – The chemical process of preparing a surface to enhance its ability to be bonded to another surface, i.e., a layer of conformal coating.

Adhesion failure – The rupture of an adhesive bond such that the separation appears to be at the adhesive-adherent interface.

Anisotropic – Having properties that vary depending on the direction of measurement.

Anthropogenic – Relating to or resulting from the influence of human beings on nature.

ARUR – Abbreviation standing for acrylic resin and urethane resin combination chemistries.

Bridging – Fillet or meniscus formation of coating around the leads of a component caused by capillary action.

Creep – Strain, deformation, or movement of coatings caused by time and/or temperature.

Cross-linking – The formation of chemical bonds between molecules in a thermosetting resin during a polymerization reaction.

CTE – (Coefficient of Thermal Expansion) Linear dimensional change with respect to an original dimension due to a change in temperature.

Cure – A change in the physical properties of a polymer by a chemical reaction.

Degradation – Decrease in quality or integrity. Loss of desired physical, chemical or electrical properties.

Delamination – A separation between a conformal coating layer and the surface it is adhering to.

De-masking – The process of removing or disengaging a maskant film, tape, boot or plug.

De-wetting – The propensity of the coating material to refuse to wet the surface evenly.

Dielectric constant – The ratio of the capacitance of a configuration of electrodes with a specific material as the dielectric between them to the capacitance of the same

electrode configuration with a vacuum or air as the dielectric.

Dielectric strength – The maximum voltage that a dielectric can withstand under specified conditions without resulting in a voltage breakdown, usually expressed as volts per unit dimension.

Dilatometry – The process of measuring expansion.

Dilution – Reduction in viscosity. Can be achieved by mixing a nonreacting, soluble agent into the material.

Dissipation factor – A value that represents the tendency of insulating or dielectric materials to absorb some of the energy in an alternating-current signal.

Diurnal – Occurring every day or having a daily cycle.

Durometer – A measure of the degree of hardness or the resistance to be deformed or fractured.

EMC – Abbreviation for Electromagnetic Compatibility

EMI – (Electromagnetic Interference) Unwanted radiated electromagnetic energy that couples into electrical conductors.

Emulsion – A stable mixture of two or more immiscible liquids held in suspension by small percentages of emulsifiers.

EOS – (Electrical Overstress) Internal result of an unwanted application of electrical energy that results in damaged components.

ESD – (Electrostatic Discharge) Rapid discharge of electrical energy that was created from electrostatic sources.

Filler – A substance that is added to a material to modify its solidity, bulk, or other properties.

Fish eyes – A surface defect to the conformal coating that resembles the eyes of a fish.

Gel time – Time taken for a liquid polymer to begin to exhibit pseudo-elastic properties or to be 'immobilized.'

Glass transition temperature T_g – The temperature at which an amorphous polymer, or the amorphous regions in a partially-crystalline polymer, changes from being in a hard and relatively-brittle condition to being in a viscous or rubbery condition.

Hardness – A property that indicates the ability of a material to resist penetration of a specific type of indentor when forced into the material under specified conditions. Indentation hardness is inversely related to the penetration and is dependent on the elastic modulus and viscoelastic behavior of the material.

Heptane – Any of several isometric alkanes C_7H_{16}; especially the liquid normal isomer occurring in petroleum and used especially as a solvent and in determining octane numbers.

Hybrid – A coating system with more than one principle resin chemistry.

Hydrolytic stability – The degree of resistance of a polymer to permanent property changes from hydrolytic effects.

Hydrophobic-oleophobic coatings – A coating having an aversion to water and oils.

Impedance – The resistance to the flow of current, represented by an electrical network of combined resistance, capacitance and inductance reaction, in a conductor as seen by an AC source or varying time voltage.

Inhibition – The inability for the coating materials to obtain the desired properties at the manufacturers' specified time and temperature.

Insulation resistance – A measure of the capability of a material to electrically insulate adjacent conductors from each other.

Masking – The process of applying a temporary film, tape, boot or plug that prevents the area covered from being coated.

Mealing – A condition in form of discrete spots or patches that reveals a separation at the interface between a conformal coating and the surface to be coated.

Monomer – A chemical compound that can undergo polymerization.

MSDS – (Material Safety Data Sheet) Provided by the manufacturer, contains relevant properties of the material with regards to safety concerns.

Multi-layering – The process of applying more than one layer of coating to make up the desired thickness.

NBC contamination – Abbreviation for Nuclear, Biological, and Chemical agents of contamination.

Oligomer – A polymer or polymer intermediate containing relatively few structural units.

Orange peeling – A surface defect to the conformal coating that resembles the surface or skin of an orange.

Outgassing – The gaseous emission from a processed coating layer when it is exposed to heat or reduced air pressure, or both.

Permeability – The ability of molecules of one material to flow through the matrix of another material. The degree of permeability is dependant on the molecular structure of both materials.

Photoresist – A material that is sensitive to portions of the light spectrum and that, when properly exposed, can mask portions of a base metal from exposure with a high degree of integrity.

Polymer – A compound of high molecular weight that is derived from either the joining together or many small similar or dissimilar molecules or by the condensation of many small molecules by the elimination of water, alcohol, or some other solvent.

Polymerization – The formation of a matrix of cross-linked long chain molecular structure from short chain monomer molecules.

Polysiloxane – A polymer whose main chemical linkage is repeating units of SiO atoms bonded together.

Pot life – The length of time a material, substance, or product can be left in an open package or dispenser, while it meets all applicable specification requirements and remains suitable for its intended use.

Priming – A surface treatment utilizing a surfactant to promote adhesion of conformal coating.

Repair – The act of restoring the functional capability of a defective article in a manner that precludes compliance of the article with applicable drawings or specifications.

Rework – The act of reprocessing noncomplying articles, through the use of original or alternate equivalent processing, in a manner that assures compliance of the article with applicable drawings or specifications.

RTV – (Room Temperature Vulcanizing) The development of desired dry film properties at room temperature

Shadowing, coating –

1. A situation that can occur during spray coating of a PCA when components may hide or "shadow" the area underneath them, relative to the spray direction, preventing the surfaces beneath the component from being coated
2. Also used in reference to curing of coatings by UV rays when components may hide or "shadow" the area underneath, not allowing it to be exposed and cured by the UV rays.

Shelf life – The length of time a material, substance, or product can be stored, under specific environmental conditions, while it meets all applicable specification requirements and remains suitable for its intended use.

Shrinkage – Reduction in volume as a wet, freshly applied layer dries/cures into a coating film with desired properties

Solids content – The proportion of 'resin' or polymer material to the solvent carrier

Spectroscopy – The production and investigation of spectra, or the process of using a spectroscope or spectrometer.

Stripping – The process of eroding a material by chemical reaction. Stripping agents can be used to remove certain types of conformal coating for the purpose of rework or repair.

Surface tension – The natural, inward, molecular-attraction force that inhibits the spread of a liquid at its interface with a solid material.

Thermoplastic – A plastic that can be repeatedly softened and reshaped, without any significant change in inherent properties, by exposure to heat and hardened by cooling.

Thermoset – A plastic that undergoes a chemical reaction when exposed to elevated temperatures that leads to it having a relatively infusible or crosslinked state that cannot be softened or reshaped by subsequent heating.

Toluene – A liquid aromatic hydrocarbon C_7H_8 that resembles benzene but is less volatile, flammable, and toxic and is used as a solvent in organic synthesis. Also known as Methyl Benzene.

Transfer efficiency – The ratio of volume dispensed to the desired volume of coating materials on the PCA

Vessication – The formation of blisters at the interface between a semi-permeable polymer film coating and another material caused by an osmotic effect from the interaction of water soluble matter with moisture.

Viscosity – The property of a polymer to frictionally resist internal flow that is directly proportional to the applied force

VOC – (Volatile organic compound) Regulated compounds containing carbon that have measurable vapor pressures.

Wetting – The formation of a relatively uniform, and adherent film of materials on a surface.

Withstand voltage – See dielectric strength.

Young's modulus – Modulus of elasticity. A measure of the flexibility of a material. The lower the modulus, the more flexible the material.

2 QUALIFICATION AND SPECIFICATION REFERENCES OF CONFORMAL COATINGS

The following documents are listed for reference only. This handbook does not attempt to explain these documents.

2.1 ASTM International Standards[1]

ASTM D570 Standard Test Method for Water Absorption of Plastics

1. Note: revision dates of the ASTM International standards are not included in their listing here. Please refer to the current revision.

ASTM D635 Rate of Burning and/or Extent and Time of Burning of Self-Supporting Plastics in A Horizontal Position

ASTM D3359 Standard Test Methods for Measuring Adhesion by Tape Test

ASTM D3833 Standard Test Method for Water Vapor Transmission of Pressure Sensitive Tapes

ASTM E96 Standard Test Methods for Water Vapor Transmission of Materials

ASTM E595 Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment

ASTM F1249 Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using Modulated Infrared Sensor

2.2 Federal Aviation Regulations (FAR)

FAR §25.853 and Appendix F FAA material flammability tests

2.3 IPC Standards[2]

IPC-HDBK-001 Handbook & Guide to Supplement J-STD-001

IPC-SC-60 Post Solder Solvent Cleaning Handbook

IPC-SA-61 Post Solder Semiaqueous Cleaning Handbook

IPC-AC-62 Post Solder Aqueous Cleaning Handbook

IPC-CH-65 Guidelines for Cleaning of Printed Boards and Assemblies

IPC-D-279 Design guidelines for Reliable Surface Mount Technology Printed Board Assemblies

IPC-A-610 Acceptability of Electronics Assemblies

IPC-TM-650 Test Method Manual[3]

2.3.25 Detection and Measurement of Ionizable Surface Contaminants by Resistivity of Solvent Extract

2.3.25.1 Ionic Cleanliness Testing of Bare PWBs

2.3.27 Cleanliness Test - Residual Rosin

2.3.27.1 Rosin Flux Residue Analysis-HPLC Method

2.3.28 Ionic Analysis of Circuit Boards, Ion Chromatography Method

2.3.38 Surface Organic Contaminant Detection Test

2.3.39 Surface Organic Contaminant Identification Test (Infrared Analytical Method)

2.5.7.1 Dielectric Withstanding Voltage - Polymeric Conformal Coating

2.6.1.1 Fungus Resistance - Conformal Coating

2.6.3 Moisture and Insulation Resistance, Printed Boards

2.6.3.1 Moisture and Insulation Resistance-Polymeric Solder Masks and Conformal Coatings

2.6.3.4 Moisture and Insulation Resistance - Conformal Coating

2.6.7.1 Thermal Shock - Conformal Coating

2.6.11.1 Hydrolytic Stability - Conformal Coating

IPC-CC-830 Qualification and Performance of Electrical Insulating Compound for Printed Board Assemblies

IPC-SM-840 Qualification and Performance of Permanent Solder Mask

IPC-2221 Generic Standard on Printed Board Design

IPC-6012 Qualification and Performance Specification for Rigid Printed Boards

IPC-7711 Rework of Electronic Assemblies

IPC-7721 Repair and Modification of Printed Boards and Electronic Assemblies

2.4 Joint Industry Standard[4]

J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies

J-STD-004 Requirements for Soldering Fluxes

2.5 Military Standards[5]

MIL-STD-202 Method 106 Test Methods For Electronic And Electrical Component Parts

MIL-C-28809 Circuit Card Assemblies, Rigid, Flexible, And Rigid Flex[6]

MIL-I-46058 Insulating Compound, Electrical (For Coating Printed Circuit Assemblies)[7]

2. www.ipc.org
3. Current and revised IPC Test Methods are available through IPC-TM-650 subscription and on the IPC Web site (www.ipc.org/html/testmethods.htm)
4. www.ipc.org
5. Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094
6. Document canceled without replacement 1995
7. Document currently inactive for new designs. http://dodssp.daps.mil/products.htm.

2.6 Underwriters Laboratories[8]

UL94 Tests for Flammability of Plastic Materials for Parts in Devices and Appliances

UL746C Polymeric Materials - Use in Electrical Equipment Evaluations

UL746E Polymeric Materials - Industrial Laminates, Filament Wound Tubing, Vulcanized Fiber, and Materials Used in Printed Circuit Boards

2.7 International Standards

2.71 British Standards (DSTAN, UK Defence Standardization)

DEF-STD-59/47 Issue 4 Conformal Coatings For Panels, Printed Circuits And Panels, Electronic Circuit *(QPL maintained, alternative to MIL-I-46058C, Independent testing and certification)*

EN 61086 (BS) Specification For Coatings For Loaded Printed Wire Boards [Conformal Coatings]

2.7.2 IEC Standards

IEC 60664 Insulation coordination for equipment within low-voltage systems

IEC 61086 Specification for coatings for loaded printed wire boards (conformal coatings)

2.8 Original Equipment Manufacturing (OEM) Specification OEM specifications are engineering documents in the form of either an engineering drawing, showing areas of electronic hardware to be conformally coated, or a text document which contains requirements and processes that conformal coatings shall meet in the "applied" condition. Specifically directed to the assembly and fabrication of hardware, these requirements are usually based on electrical output, physical performance, life cycle reliability of a PCA in an end-use environment. Since each PCA is unique in its functional and electrical responses, conformal coatings have to be selected for usage based on their ability to perform as a protective coating without deleterious effects upon electronic circuit elements over the PCAs performance and life cycle requirements while also meeting the material property and compatibility of the conformal coating to the PCA substrate surfaces.

3 ENVIRONMENTAL, HEALTH AND SAFETY CONSIDERATIONS

Recent environmental regulations such as the Montreal Protocol and Clean Air Act have had a significant impact on both coating materials and application methods, particularly with regard to control of volatile organic compounds (VOCs) and ozone depleting chlorofluorocarbon (CFC) compounds. VOCs can be defined as any solvent that has a vapor pressure greater than 0.001 mPa [1.45 x 10^{-10} PSI] and are the primary concern, as they react in the atmosphere to form ground level ozone (or smog). CFCs have been found to deplete earth's protective ozone layer in the upper stratosphere. Both VOCs and CFCs have been extensively used as solvent carriers. Manufacturers and suppliers of conformal coating materials have responded by developing nonsolvent based coatings and environmentally acceptable methods of application, curing and removal.

Specific environmental, health and safety concerns are addressed in various subsections. Refer to 9.13 for processing considerations and 11.4 for rework and repair issues.

3.1 Emissions Emission is defined as any substance discharged into the atmosphere such as solvents in conformal coating systems, fluxes, cleaners etc. Certain types of solvent such as isopropyl alcohol, xylene, etc. are volatile organic compound (VOC) liquids containing carbon and hydrogen that emit VOC vapors.

3.2 Disposal of Hazardous Waste Hazardous waste is defined as any material that is classified as such and stated on the manufacturers material safety data sheet (MSDS). Disposal of hazardous waste should be in total compliance with the local, state and federal regulations.

3.3 Governmental Regulations The user should be aware of any limitation with the use of any product or material used in their process. Frequently asked questions about hazardous waste are answered on the Environmental Protection Agency's website at http://www.EPA.gov.

4 TYPES OF CONFORMAL COATINGS

Conformal coatings are polymeric materials used to protect electronic assemblies from a wide variety of life cycle contaminants. Conformal coatings provide a high degree of insulative protection and are usually resistant to many types of solvents and harsh environments encountered in the product life cycle. The coating materials also act to immobilize various types of particulates on the surface of the PCA and function as protective barriers to the various devices on the board.

They are resistant to moisture and humidity, which may reduce the potential of leakage currents, "cross talk," electrochemical migration, dendrite growth and arcing. These issues are becoming more critical with the reduction in component size, pitch, circuitry spacing, laminate thickness, and voltage plus the rise in speed (frequency) of signals.

8 Underwriters Laboratories Inc., 1285 Walt Whitman Road Melville, Long Island, NY 11746

Conformal coatings can be broken down into two liquid families, organic and silicone. The primary traditional classifications are acrylic (AR), epoxy (ER), silicone (SR) urethane (UR) and poly-para-xylylene (XY). Figure 4-1 illustrates these classifications based on basic resin chemistry type, which is further differentiated into subtypes based on cure mechanism. Appendix A provides a comparison of various product types as a quick guide for the selection of conformal coating.

These systems are primarily made up of monomers, oligomers, de-foaming agents, fillers, and wetting agents. There are also water-based emulsions. Various combinations of each are added to the formulations to adjust the cured and uncured properties. Solvents may be added to adjust application viscosity. Prior to the start of curing process, solvents evaporate ("flash off"), leaving a resin matrix to initiate the cure. The VOC emissions associated with this type of cure created a need for more environmentally

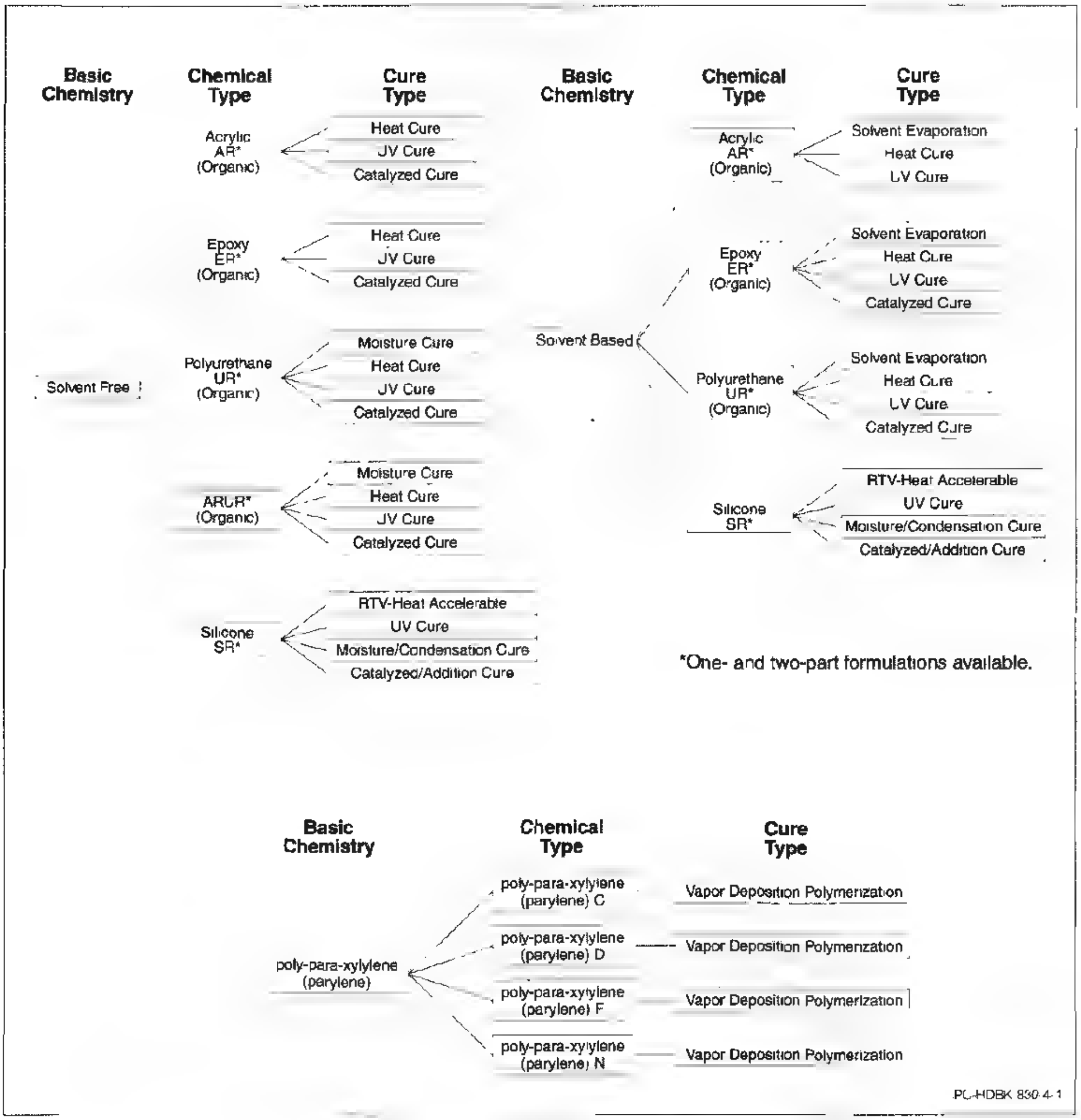

Figure 4-1 Conformal Coating Family Trees

acceptable production chemistries and cure mechanisms. Presently, solvent and water-based conformal coating chemistries exist which are exempt from environmental regulations. See Sections 3, 8.13 and 10.4 on environmental, health and safety considerations.

All resins except for acrylic resins are cured by an irreversible polymerization reaction with varying degree of cross-linking (thermoset polymers). The cross-linking of the epoxy, urethane, and silicone polymers provide very good chemical resistance but also make it difficult to remove the coatings when performing repair work. No polymerization reaction is taking place when applying acrylic coatings. Therefore, it is misleading to say that acrylic coatings are cured. They are formed by drying a solution of already formed acrylic polymer chains dissolved in a solvent (thermoplastic polymer). Hence, acrylic coatings are easily dissolved in many organic solvents providing selective chemical resistance but facilitating repair work. Consequently, acrylic materials are either solvent or water-based.

All, except the poly-para-xylelenes (parylenes), have traditionally been solvent based until a decade ago when environmental issues dictated a need to change. Now, many materials are solvent-free chemistries (100% solids). The ability to ultra violet (UV) cure is commonplace. This new generation of conformal coating materials has also given birth to hybrid coatings that contain two or more systems to achieve superior properties, i.e., ARUR. See 4.6 for examples of two-part systems.

Raw materials as well as film properties need to be considered while selecting conformal coating materials. Due to variations in conformal coating chemistry, it is recommended to consult the coating manufacturers or technical data sheet for more information.

4.1 AR – Acrylic Acrylics are easy to apply and the dried film can be removed using the solvent method in Section 11 Rework and Repair. Spot removal of the coating to repair a solder joint or replace a component can be easily accomplished by localized solvent application. Though not encouraged, they may be soldered through if preferred.

Acrylics dry rapidly, reaching optimum physical properties in minutes, are fungus resistant and provide long pot life. Furthermore, acrylics give off little or no heat during cure, eliminating damage to heat-sensitive components, do not shrink during cure and have good humidity resistance. Acrylics tend to soften more readily at elevated temperatures than other polymers.

4.2 ER – Epoxy Epoxy systems are usually available as two part compounds. They provide reasonable humidity resistance and good abrasive and chemical resistance. They are virtually impossible to remove chemically for rework since any stripper that will remove the coating may vigorously attack epoxy-potted components as well as the epoxy-glass board itself. The only effective way to repair a board or replace a component is to burn through the epoxy coating with a knife or soldering iron.

Single part epoxy resin coatings with temperature-activated hardeners are also available. These coatings require curing at temperatures higher than 66°C [150°F]. Single part UV curable coatings are available which eliminates curing at these elevated temperatures.

When most epoxies are applied, a 'buffer' material should be used around fragile components to prevent their damage from film shrinkage during polymerization. Curing at low temperature, if possible, is encouraged to reduce shrinkage.

Curing of epoxy systems takes place up to three hours at an elevated temperature or up to seven days at room temperature. Short pot life creates a limitation on their effective use.

4.3 SR – Silicone Silicone coatings are extremely useful materials when components will endure extreme temperature cycling environments such as automotive applications. The useful operating range of these materials is -55°C to +200°C [-67°F to +392°F]. They provide high humidity resistance along with good thermal endurance, making them desirable for PCAs with heat dissipating components such as power resistors. For high impedance circuitry, silicones offer a very low dissipation factor. They are very forgiving materials in production because they coat over and adhere to most surfaces found on a PCB and offer good resistance to polar solvents. Cross contamination factors stemming from the use of silicones and the effects on other production processes is no longer a major concern with the solvent-free, nonvolatile chemistries that are easily handled with proper housekeeping practices. Secondary cure for the UV curable versions is accomplished with a very effective ambient moisture mechanism. It should also be considered that high temperature protection may generally demand that the silicone coating be cured at or near to the maximum temperature it is designed to withstand. Silicone coatings can be applied at large thickness >0.3 mm [>0.01 in], thus immobilizing wiring (jumpers etc.) on PCAs.

4.4 UR – Polyurethane Polyurethane coatings are available as either single or two-component formulations. Both provide good humidity and chemical resistance, plus higher sustained dielectric properties.

Their chemical resistance, however, can be a major drawback since rework can become difficult and costly. To repair or replace a component, refer to Section 11 on Rework and Repair.

Early polyurethane compounds exhibited instability or reversion of the cured film to a liquid under high humidity and temperature conditions. Newer formulations, however, eliminate this phenomenon.

While polyurethane's can be soldered through, this usually results in a brownish residue, which affects the aesthetics of the coating.

Single component polyurethane's, while easy to apply, sometimes require 3-30 days at room temperature for optimum cure. Two component formulations, on the other hand, reach optimum cure properties at elevated temperatures within 1-3 hours, but with pot lives of 30 minutes to 3 hours.

4.5 XY – Poly-para-xylelene (parylene) These are the vacuum deposited poly-para-xylelene (parylene) coatings. Both material characteristics and application technique yield XY conformal coatings that are uniquely different from the liquid applied coating types. The obtained coating film yields consistent thickness with true conformance to PCA contour and is pinhole and bubble free. The XY film is also characterized by properties such as good dielectric, low thermal expansion, good abrasion resistance and outstanding chemical resistance, among others. This makes XY coating a good choice for protecting circuits against effects from harsh environments, notably high humidity with condensation, intermittent immersion, salt fog, atmospheric pollutants and exposure to aggressive solvents. This type of coating is frequently used in FDA approved devices for medical and biomedical applications. Poly-para-xylelene (parylene) coating can be removed by abrasion, conventional surface mount techniques, excimer laser, heat softening, plasma etching and several other methods. Poly para-xylelene (parylene) coatings are very effective in high voltage applications, owing to the capability of coating sharp edges.

A fluorinated version is also available that can maintain its properties at temperatures in excess of 400°C [752°F], has increased UV stability, and has a lower dielectric constant. Poly-para-xylelenes will not readily adhere to ionic residues and they exhibit poor repairability in comparison to the other coating types. The repaired coating often does not return the protection to a monolithic film. Poly-para-xylelenes require masking of components that are not to be coated. The masking must be 100% effective for the vacuum coating process.

4.6 Two-Part Systems (Acrylic/Polyurethane and Other Combinations)

4.6.1 UV and Solvent Cure One method of curing uses ultra violet light. This permits curing of the material in seconds rather than in minutes or hours. They have been specifically developed for use on flat bare substrates and are of particular benefit for fiber optic filament coating as curing can be effected at speeds of up to 122 m/min [400 ft/min].

Their use on PCAs, however, is somewhat limited because of the shadowing effect produced by components. As a result of this, a catalyst is often required to ensure a chemical reaction to cure the compound in shaded areas. However, this produces the associated drawbacks of two-part systems such as short pot life and material blending for correct application. One-part materials have been developed, although they tend to be of an epoxy or polyurethane base.

Two-part products are difficult to repair as subsequently reapplied coatings do not etch into the existing material surface, but produce discrete lamination. The reliability of this type of coating is suspected at temperatures below -55°C [-67°F] or above +130°C [+266°F] because the coating may become brittle and less flexible.

4.7 Other Types of Conformal Coatings

4.7.1 Fluorocarbon (FC) Fluorochemical surface modifiers are hydrophobic-oleophobic coatings that reduce the surface energy of a substrate to 11-12 mN/m. This property allows water, solvents such as heptane, toluene and acetone, and lubricating oils to bead up and drain off a substrate. These coatings are applied as a thin fast drying layer that can be soldered through for rework, and frequently do not require masking. The coatings are typically supplied in fluorocarbon solvents which are nonflammable, low in toxicity and are not VOCs. The low viscosity and low surface tension of the coating allows it to flow into, and coat in-between, small gaps and layers. Fluorochemical surface modifier coatings are thin and not very resistant to abrasion, but insoluble to most organic solvents and as a fully reacted polymer in solution, has an indefinite pot life.

These coatings are generally unsuitable for applications where the operating temperature exceeds 40°C [104°F] because the material begins to volatize beyond this point.

4.7.2 Perfluoroether For certain applications involving extended exposure to fuels, hydrocarbon oils, hydraulic fluid, nonpolar solvents, acids or bases, the use of perfluoroether type coatings could be considered. This polymer is based on a perfluoroether (fluorinated-carbon to oxygen) backbone combined with an addition-curing silicone crosslinker. One-part perfluoroether materials are processed (dispensed/sprayed and cured) in the same manner as heat-cured silicone type coatings. They can be sprayed or dispensed using typical existing equipment and heat cured at 150°C [302°F] for one hour.

Perfluoroether elastomer provides improved low temperature properties, long-term heat resistance, self-priming adhesion, excellent electrical properties, and ionic purity. As a 100% solids (no-solvent) material, it offers processing advantages unmatched by other standard fluoroelastomers. The thermal resistance and low modulus are similar to silicone properties while providing protection from the harshest environments.

5 DESIGN FOR COATING APPLICATION

This section establishes design concepts, guidelines, and procedures intended to promote appropriate "Design for Reliability (DfR)" procedures and to ensure reliable characteristics of a conformal coated printed circuit assembly (PCA).

The definition of reliability in this section is: Reliability is the ability of a product to function under given conditions and for a specified period of time without failure.

This section addresses reliability-related aspects of product design, process design, as well as material/component selection and qualification when using conformal coatings in accordance with the design guidelines given in IPC-D-279. This section also identifies other appropriate exiting IPC documents as reference for basic detailed information. The effort of this section is directed at making the designer and the users of conformal coatings for electronic applications aware of the various factors that affect the protection afforded coated PCAs in the end-use environment for the design-life of the PCA.

5.1 Design Philosophy Before the product design effort can begin, the designers of the product and assembly process need to know the customer's reliability requirements for the product. These requirements should be defined and ranked by a concurrent engineering or cross-functional team through a process such as Quality Function Deployment (QFD) used to capture the voice of the customer.

The design team can include, but is not limited to, the members who participate in at least the design activities identified in the IPC-D-279. In this table, DfA/M stands for Design for Assembly/Manufacturability, DfT for Design for Testability, DfR for Design for Reliability.

The design team can consider the general design guidelines presented in the body of this section as a methodology for achieving its reliability goals. The IPC-D-279 contains information that illustrates the general design steps and process flow using concurrent engineering. The IPC D 279 also includes information that illustrates the interactive nature of the design for reliability process.

5.1.1 Defining Reliability Requirements The basic requirements to be defined include but are not limited to:

- Years of service.
- Failure rate(s)/probability(ies) as a function of time
- Repair/replacement/upgrade/service/maintenance/warranty strategy.
- Life cycle environment(s).
- Definition of acceptable performance.
- Criticality of function(s).
- Available test equipment.
- Mean time between maintenance
- Mean time between failures.

5.1.2 Understanding the Product Life Cycle The product life cycle begins at the component level (including the printed board) and continues through and beyond the assembly level. Exposures throughout the life cycle include the assembly/process conditions; the testing, storing, transportation and operating environments.

Test, storage and transportation need to be considered at both component and assembly levels as well as before, during, and after the coating process

5.1.3 Defining the Product Environment For each environment in 5.1.2, it is critical to identify, characterize and quantify all the parameters that may affect the performance of the product. These include the humidity and pressure of the environment; the range, rate of change and exposure period to temperature, i.e., temperature cycles encountered during the operation of the product Some products may also encounter physical vibration and shock during operations. Electrical parameters such as ESD, EOS, EMC, EMI and high voltage exposure should be taken into consideration Most environments impose a certain level of chemical exposure from either some common factors such as salt spray and fuel, or specific chemicals such as flux, solvents, NBC decontamination, etc. Not to be neglected are radiation from sun light, UV or other specific sources, reactive gases (SO_x, NO_x, H_2S, Cl_2, O_3, etc.), airborne/surface acids, submicron particles, and contamination from dust, oil or human contact.

When the life environments have been identified and defined, the engineering team is prepared to analyze and select the conformal coating, coating process, and test strategies required.

5.2 PCBs\Printed Circuit Boards (PCBs) are one of the major subcomponents of a conformally-coated printed circuit assembly (PCA) Other sub-elements of the PCA that are considered in the conformal coating design and selection include, but are not limited to, surface finish, spacing between component leads or printed circuit features, discrete and integrated circuit components, solder joint configuration, etc. However, it is the PCB that is the singular largest feature of the PCA that is conformally coated and therefore has a significant impact in determining which conformal coating and process of application is most appropriate to use. The characteristics of the PCB that need to be considered should include the properties of the dielectric laminate, prepreg adhesive, metallized signal layers, pad pattern for surface mount attach designs, aspect ratio of plated-through holes (PTH) and vias (blind or buried). Therefore, the materials of construction of the PCB are important in determining the appropriate conformal coating and method of application to use.

5.2.1 Plating Surfaces Plating surfaces are the metallic areas that remain on the exterior surface of the PCB as well as through-holes and solder pads after etching and removal of photoresists These areas are typically bare copper that are then plated with tin/lead (Sn/Pb) In some cases, large metallic areas are often plated with other organometallic metals such as nickel or even solder mask. In most of these instances, the plated surfaces will have some dissimilar metal interfaces that will be coated with a conformal coating. In addition, there may be designs in which a conformal coating will either partially or completely cover the plated surface areas. In situations with partial coating coverage, the edge of the coating may delaminate or lose adhesion to the surface of the plated metal

5.2.2 Alternate Surface Finishes One of the areas on a PCA that a conformal coating has to adhere to is the surface finish of the PCB. Surface finish is the material on metallized areas of the exterior PCB layer that usually results during bare board manufacture. Previous generations of these areas on a PCB where the remaining copper after etching and other PCB processing prior to reflowing tin/lead (Sn/Pb). Newer technologies have resulted in alternate materials to Sn/Pb being used as the finish on the PCB prior to assembly processing These materials include, but are not limited to, bare copper, immersion tin, immersion silver, immersion gold, electrolytic or electroless nickel combined with gold and/or palladium, organic soldering preservative (OSP), and other similar types of alloys.

In many situations, some surface finish areas are not being changed when there is no solder joint formation and therefore are part of the overall board substrate. Depending on the type of board surface finish, there may be dissimilar metal interfaces that could lead to corrosion if not protected from humid environments Conformal coating materials would then need to be considered as a corrosion prevention aid in addition to an environmental protection barrier. The dissimilar metal combination of an alternate surface finish over bare copper is also a surface in which conformal coating adhesion may also need to be evaluated.

In many cases, these conditions may necessitate conducting a qualification test using a representative PCB sample before approving the intended conformal coating as "acceptable for use."

5.2.3 Spacing Reduced heat extraction from the PCA (and increased junction temperatures) may result if conformal coating covers heat conduction surfaces on the PCA edge or margin which mate with heat sinks such as card-edge clamps and cold plates. A resolution is to widen conductors that function as heat dissipaters. If possible, it is recommended to limit ΔT conductor to less than 5°C [41°F]

The other issue concerning the aspect of spacing on PCAs involves the areas between adjacent printed circuit traces or between solder pads at the PCB level Other spacing issues are the physical volume between adjacent leads of soldered electronic components. In all these instances, a conformal coating is usually required to cover these areas. For soldered components with leads, they usually require complete coating coverage without solder bridging in between adjacent leads to maintain the necessary dielectric insulation. The type of conformal coating that would be used usually depends on spacing between the leads (lead pitch) and whether the leads are cylindrical or rectangular. For fine pitched leaded devices the finer the pitch, i e., smaller spacing and clearance between adjacent leads, a coating with lower viscosity should be considered to achieve uniform thickness while providing edge and point coverage.

5.2.4 Solder Mask Compatibility issues between solder mask and conformal coating should be considered when designing a PCB for conformal coating application. Refer to 8.1.1 for solder mask material compatibility.

5.3 Component Various different types of component packages are widely used in electronic circuitry. The materials used in packages vary greatly and consist of mold release agents, waxes, plastics, ceramics, marking inks, metals, glass and various other materials. The degree of conformal coating adhesion, CTE mismatch, shear modulus and general wetting characteristics of these materials need to be considered when application of conformal coating is anticipated

Over-application of conformal coating materials (excess thickness) could be detrimental to long-term reliability for most leaded and leadless components, except dam and fill and glob top types of components.

5.3.1 Component Material Type

5.3.1.1 Plastic Various mold release agents are used to assist in the release of these packages from the mold after the injection molding process. Component suppliers consider these release agents proprietary and are reluctant to reveal the exact formula used, commonly these are silicone based products. These agents may impact the degree of wetting and the adhesion of conformal coating (or any adhesive) to the package. The plastic packages may absorb various process materials such as fluxes and cleaning agents, and the release agents may exit the porous plastic matrix in subsequent heat excursions in processes or end use environments.

5.3.1.2 Ceramic Ceramic packages typically do not pose much of a threat to most conformal coatings. They are sometimes color-coded and the pigments should be considered, but they rarely pose problems with the conformal coating. Marking inks, however, may contain polysiloxane agents, which may cause de-wetting and adhesion loss of

the conformal coating, but usually only occurs in the proximity area of legend markings.

5.3.1.3 Metal Metal packages are of the least concern of all types of package materials currently used. Most conformal coating formulations are designed to wet and adhere well to these surfaces. The marking inks and/or decals used should be considered as localized de-wetting and/or delamination may occur.

5.3.1.4 Glass Glass components, such as diodes, typically pose no threat to conformal coating application and adhesion. The primary concern should be the coating fillet surrounding the component. Too thick a cured liquid coating fillet can cause stress to the component body and crack and/or weaken the solder fillet as a result of extreme temperature cycling. Low modulus "buffering" compounds can be used as an adjunct in end use applications consisting of high vibration and thermal cycling.

5.3.2 Through-Hole Components Through-hole components are devices that penetrate substrates via holes in the boards. They can have multiple leads and are composed of various metals and placed through a "tinning" process prior to insertion that enhances the solderability of leads. Once parts are inserted, the leads may be clinched and clipped. After soldering operation, the clipped leads typically create sharp edges on the bottom side of the PCA. These could be difficult areas to cover with conformal coating. Liquid conformal coatings typically do not build up on the sharp edges because gravity moves them to the base of the lead and solder fillet. When it is cured, very little coating material would be left on the edges of clipped leads.

Abrasion of the coating at lead edges due to subsequent handling should be considered. The type of coating chemistry, application method and cure mechanism dictates the success of creating film buildup in these areas. Multiple coats and higher viscosity coating is typically recommended for pin cover.

Fluxes used during a wave soldering process often 'wick' up the legs of such components and onto the 'top-side' of the assembly surface. This may lead to coating reliability problems caused by the flux residues if a no-clean process is being used.

5.3.2.1 Axial Leaded Components Axial components are leaded through-hole devices. They are typically bent at a 90-degree radius and inserted into holes in the board. They may be clinched, cut and soldered. Since most are cylindrical in shape, conformal coating concerns include enormous fillet formation under and around these types of devices. This may create shadows during the curing process of single component UV conformal coatings. It may also cause stress on the component body due to CTE mismatch. Axial leads typically have thinner coatings than planar sites because gravity forces wet coating to flow off and down to the solder fillets. The time elapsed from coating application to cure or coating immobilization may also affect the finished coating thickness in the actual lead areas. This is a particularly important issue if solvent-less coating materials are being used.

5.3.3 Leaded SMT Components Devices with terminations formed independently of and projecting away from, the component bodies are specified as leaded. The shape (gull wing, "J," etc.), and length of the terminations may determine the actual conformal coating thickness achieved on these types of leads. The time elapsed from coating application to cure or coating immobilization may also affect the finished coating thickness in these leaded areas.

The "pitch" or distance between leads is also a design concern for coating. Some higher viscosity coating materials may not penetrate past and under fine pitch leads and not migrate under the device. This causes bubbles to form in the coating during cure as air voids under the device heat up and the air attempts to escape from under the component. If the bubble does not pop before polymerization, it can bridge conductors and limit the degree of insulation provided by conformal coating within the cured bubble.

5.3.4 Leadless SMT Components Components with terminations formed as an integral part of the body are specified as leadless. This would include BGA, PGA, and Flip Chip, chip scale package (CSP), chip on board (COB), leadless chip carrier (LCC), and chip type components.

5.3.4.1 Ball Grid Array (BGA) Ball Grid Array devices are leadless. They contain solder bumps on the underside, which can be peripheral or area dispersed. The finished gap under the device after solder collapse can be 0.5 mm [0.020 in] to 1.3 mm [0.0512 in]. This is generally enough to allow good capillary flow of conformal coating under the device depending on how large the BGA is. BGAs in excess of 650 mm^2 [1.007 in^2] may limit the amount of coating penetrating under the device via capillary flow. Post soldering residues are of prime concern as cleaning and inspection under these types of devices can be difficult or even impossible. Many of these devices are now being "under-filled" with epoxy prior to the conformal coating operation.

5.3.4.2 Pin Grid Array (PGA) Pin Grid Arrays are similar to the BGA except for the fact that pins have replaced the solder bumps. The characteristics affecting the conformal coating are identical to those of the BGA.

5.3.4.3 Flip Chip (COB, CSP) Flip Chip devices are package-less die, which have been bumped with solder on the contact sites. The solder bumps are fluxed and the silicon chip is inverted, placed and passed through solder

reflow The device is then "underfilled" with an epoxy creating a complete seal and fillet around the device. The conformal coating can be applied over the die. Adhesion and wetting to the epoxy underfill fillet is usually not an issue

Underfill can also be applied at the wafer level with B-staged anisotropic adhesives. Some versions also contain flux within the epoxy matrix, hence "fluxing underfills" which eliminate the fluxing step.

5.3.4.4 Dam and Fill This type of device is similar to flip chip except the die is turned face up and still contains wire die bonds Because of this, it can be considered a leaded device before encapsulation.

The die is connected on the bottom side with die attach adhesive which is usually a conductive epoxy. The wire die bonds are made from the die face to the substrate or lead frame. Using a high viscosity epoxy, a dam is dispensed around the outside parameter of the device. The height profile of the dam should exceed the tallest die wires. A second epoxy material, which is low in viscosity, is then dispensed within the dam parameter and both materials are cured simultaneously. This completely encapsulates the device. Rework is not practical.

The conformal coating should primarily be used to protect other conductors and leaded devices on the board If coated, the dam and fill epoxy package does not generally pose wetting or adherence problems with the coating.

5.3.4.5 Glob Top Glob top is similar to dam and fill with the only difference being a high viscosity epoxy encapsulant is dispensed in the center of the die. The epoxy should encapsulate the wire die bonds without breaking the fine leads and flow over the entire device. It is then cured. The height profile of the epoxy glob needs to exceed the highest bend in the die wires by 30%. Glob-tops are not to be confused with conformal coatings as they perform fundamentally different functions.

5.4 Electrical The effect of conformal coating on the electrical functioning of a PCB can be either beneficial or detrimental This depends primarily on the design parameters of the circuit and the material of the conformal coating. How beneficial or how detrimental depends on good engineering, as outlined below

There are several distinct categories of electronic circuits/assemblies that will be briefly discussed with regards to the possible effects of conformal coatings. These include high voltage, high current, RF and microwave, high speed digital, along with the effect on ESD and EMI. The effects discussed only apply to circuit traces on the outer layers of the PCB. In other words, those traces in direct contact with the conformal coating.

5.4.1 High Voltage (HV)/High Current (HC) High Voltage (HV) circuits are the one case where conformal coatings may be necessary for the PCA to function in some environments. Conformal coatings are used to provide greater insulation between HV leads than is provided by the air Such additional insulation is needed to prevent HV arcing, corona and St Elmo's Fire. The best method to produce HV circuits with a high degree of robustness is by using conformal coatings or other encapsulates after assembly. Conformal coating is not to be used in lieu of electrical insulation on high voltage wire.

Therefore, an important characteristic of a conformal coating used in HV circuitry is its dielectric strength. Given the dielectric strength of the conformal coating material and the maximum voltage of the circuit, the necessary thickness of the coating can be calculated from:

$T = V \times 6.44 \times 10^{-6}$

Where T is thickness in inches of the coating and V is the voltage in volts. With HV circuits it is the ability to contain the HV that is critical.

For High Current (HC) circuits, on the other hand, conformal coatings are generally detrimental. High current means high heat and conformal coatings interfere with the dispersion of that heat. Therefore, good thermal conductivity is the key property for coatings used in high current circuits. Other important factors include high melting point and glass transition temperature (T_g). If the melting point and/or the T_g are too low the coating may melt or deform from the dissipated heat.

Circuits which are both high voltage and high current need conformal coatings with both good electrical insulation to contain the HV and good thermal conductivity to dissipate the heat generated by the high current. Unfortunately, materials that are good electrical insulators are typically not good thermal conductors. Therefore, tradeoffs are required based upon the design of the circuit, how it will be used, environmental conditions, etc. Good engineering in board design, component selection, as well as materials, is necessary to produce the best PCA

When seeking a conformal coating to aid in protection against a lightning strike, for components such as connectors, then a film thickness as little as 0.5 µm [12 mil] may be adequate Refer to withstand voltage of the coating material

5.4.2 RF and Microwave The materials used in a PCA can effect the propagation of RF and microwave signals in a variety of ways. For conformal coatings, the preferred effect would be none at all, or failing that, a well understood, reproducible change in performance.

Ideally, the dielectric constant of the coating material should be as close as possible to 1, that of a vacuum, and

it should absorb as little as possible of the RF energy. In practice, RF design engineers use materials whose effect on their circuits they are familiar with and which they can predict and, if necessary, correct. This makes RF designers, who usually are not very knowledgeable about materials, very cautious about trying new materials Adding to the problem is the fact that no material behaves in exactly the same manner across the entire RF and microwave frequency bands. This means that circuits in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands employ different materials than circuits in the microwave and millimeter bands. Any material whose dielectric constant changes dramatically over frequency should be avoided in very broadband applications

For conformal coatings then, a few general rules may be given It should have a dielectric constant close to 1. It should have low RF absorption. Polyurethane based 'foams' have traditionally yielded good results in these circumstances. If a conventional conformal coating is being used, it is important that it be applied evenly and at controlled thickness. Finally, it should do all these things across a usable portion, at least an octave, of the RF spectrum. Acrylics and polyurethanes are the more commonly used coatings mainly because of ease of use, repeatability of deposition and the variety of formulas allowing optimum performance across a number of frequency bands. To achieve an even application, coatings applied with vacuum deposition are often the better choice.

5.4.3 High Speed Digital In many ways, the requirements of a conformal coating for high speed digital applications are the same as those of an RF circuit of the same frequency.

Microprocessor and High Speed Digital signals reaching 10 Giga Bites Per Second may benefit from acrylics or polyurethane coatings It is important to note that AC currents induce electrons at the periphery of the conductor rather than in the center Consequently, the edge of an AC conductor is an area of higher potential for electro-chemical reactions, as the consequence of unwanted residue, than with DC current.

5.4.4 Controlled Impedance In 6.4.2 RF and Microwave, it was stated that coatings would ideally have a dielectric constant of 1, so as to alter the parameters of the circuit as little as possible. Sometimes however, it is desirable to alter the parameters, especially the circuit impedance. One method of changing the circuit impedance is to intentionally use a coating with a dielectric constant greater than 1. In the case of a microstrip the formula [9]

$$Z_0 = 377 \frac{h}{w} \left(\frac{1}{\varepsilon_r} \right)$$

gives the characteristic impedance of the microstrip. Here h is the height of the strip above it's ground plane, w the strip width and ε_r the relative dielectric constant of the PCB base material When a conformal coating is applied, the term ε_r must be changed to ε_{eff} and must be calculated taking into account the dielectric constant of both the base material and the coating The added coating will raise the "Effective Relative Permittivity" (ε_{eff}) of the environment as seen by the transmission line (trace and its signal return path). Theoretically, the impedance of a system can be altered at will by choosing the correct material, with the correct dielectric constant. In practice, few materials allow such fine-tuning and tight control of their dielectric constants. This is especially true of 2-Part conformal coating mixtures. Even with the best automatic dispenser, some parts of the board may get more of one part than another causing the dielectric constant to vary widely. Homogeneity and reproducibility are the most important characteristics for any coating material. In general silicone materials produce good results but the range of dielectric constants (5-10 usually) is rather narrow. Acrylics and epoxies need careful manufacturing to assure homogeneity but otherwise are useful and can be obtained in a wider range of values. Vacuum deposited coatings have good results with homogeneity and reproducibility as long as the process parameters remain constant.

The presence of the coating will raise the dielectric constant of the environment. The end result is that the transmission line impedance will be lower than it would be without the presence of the coating. The closer the coating's dielectric constant is to 1, the less the effect on impedance. To prevent 'Return Loss' or Voltage Standing Wave Ratio (VSWR), this effect should be understood and considered during the design process. [10]

The coating will have the same effect on the impedance of a high speed digital circuit The difference being that the end result is usually less dramatic in high speed digital applications, because digital circuits have a much greater tolerance to signal reflections and noise than do analog circuits As a rule of thumb, coatings will lower trace impedance by 1 to 3 ohms, depending on thickness and dielectric constant of the coating material relative to the thickness and dielectric constant of the PCB material between the trace and its return path (power or ground plane) Even though the coating effect is less dramatic on signal integrity in digital applications, it should be understood and considered.

5.4.5 EMI/ESD Electronic assemblies that are going to be handled, repaired, modified or etc. on a regular basis need some protection from the discharges produced by handling. The standard model used in ESD control is the

9 Reference Data for Radio Engineers, ITT: Sixth Ed. Howard W Sams & Co.
10 For exact calculations, refer to "Transmission Line Design Handbook" by Brian C Wadell (ISBN 0-89006-436-9)

human body model consisting of a 15pF capacitor through a 1500 ohm resistor at a maximum of 35KV[11]. This means that the coating should withstand high voltage but *with* only a small amount of charge behind it. Therefore the recommendations given in 6.4.1 are just as applicable here Coatings are *not* commonly used for ESD protection.

On the other hand there is little a conformal coating can do to alleviate EMI. Many items need to be understood to properly control EMI. One of those items is how to properly shield a PCA to prevent radiation of EMI or susceptibility to EMI. Shielding an PCA from EMI requires enclosing the PCA in a conductor that is then connected to ground. In theory a conductive coating could do an excellent job, but in practice the likelihood of short-circuiting leads of the various components makes this an impractical process. It is important to select a conformal coating material that does not exacerbate this problem

5.5 Coating Coverage Responsibility to specify the areas of 'where to' and 'where not to' coat should lie with the design team with consideration of the end use environment. The following are some factors to be considered

- All solder joints and exposed leads should be coated.
- Bare board areas with no traces or joints are not necessary to coat, but *may* be considered optional, if for cosmetic purposes only.
- Coating for cosmetic reasons may adversely affect assembly cycle time and usage cost.
- Component packaging.

Typical examples of areas free from coating would be: connectors, test points, variable value components, grounding points, switches, display screens, socket contacts, mechanical interface areas, etc.

Masking prevents conformal coating from being applied in a specific area. However, a masking process can be labor intensive, especially around intricate assemblies Therefore, minimizing masking should be a consideration while designing a PCA. Choosing a mask that is easy to apply and remove could be helpful in the event that masking is needed.

Users are cautioned that certain types of masking such as liquid masking materials that subsequently harden to a rubber-like consistency can cause problems in the event that they are not completely removed from electrical contacts in connectors, sockets, and other similar electrical interface areas. There is good evidence that most synthetic-based latex masking compounds can aggravate the development of electrochemical reactions on the assembly surface.

5.6 Masking The purpose for masking is to prevent certain areas on a PCA from being coated. The conventional way of specifying information on masking areas is to use a combination of a pictorial diagram and a written specification. The pictorial diagram is a very common method of demarcating the "coating-free" zones and thus the areas that need to be masked Masking and de-masking is a labor intensive process. PCAs should be designed with conformal coating operation in mind such that the number of areas that need to be masked is *minimized*. The written specification contains information on how to use various masks and more importantly the sequence steps especially when different types of masks are used. Usually the written specification also contains information on which masking techniques are acceptable to use. All this information (pictorial and written) is essential to prepare the PCA for conformal coating application.

Example of an assembly drawing with masking requirements is shown in Figure 5-1

Annotations describing the components in more detail often help. For example if only the pins in a connector housing need to be free of coating then state this, otherwise the whole connector may be masked.

It is preferable that a view of both sides of the PCA is given.

5.7 Drawings & Design Guidelines In order for a conformal coating to be used on a PCA, there should be a reference to a material and process specification as well as a pictorial drawing. The material specification usually governs all the requirements for the conformal coating material. The process specification usually identifies all the requirements associated with applying the coating material. This specification should also include details for processes preceding and subsequent to the coating step Examples of these would include but are not limited to cleaning after soldering, masking, handling (as ESD safe), de-masking and inspection. A pictorial diagram, as a guideline, should indicate either by chainline, hatched region, or *something* similar, the areas to be conformal coated

Design guidelines for conformal coating usage should always include a checklist of requirements that need to be examined. In most cases trade studies are performed to assess whether an PCA requires conformal coating coverage and if necessary which conformal coating type and processes should be used. This checklist should take into account all conventionally used design criteria/guidelines considered to be typical engineering practice.

5.8 Reworkability/Repairability If a PCB and/or the components are to be replaced during the life of the product, then the conformal coating removal and application

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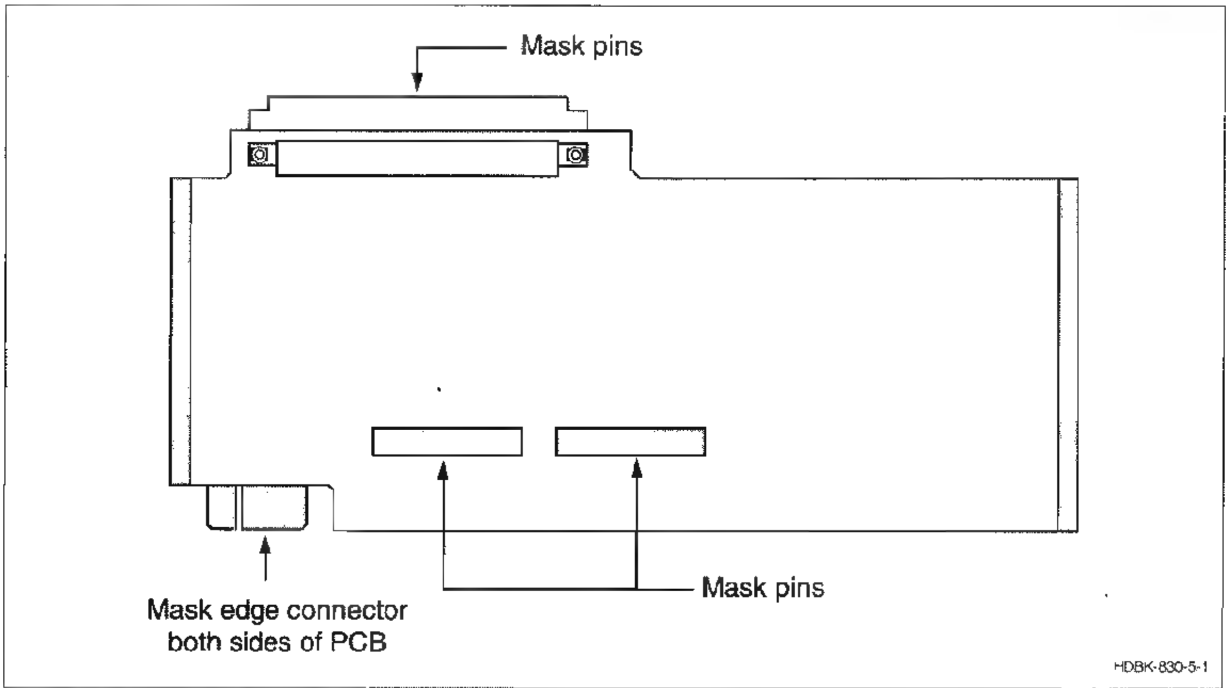

Figure 5-1 Assembly Drawing with Masking Requirements

procedures should be considered during the product design stage. The first consideration should be the post rework/repair performance as critical or noncritical. Except for acrylic coatings, it is unlikely that subsequent repair coatings will regenerate a monolithic, homogeneous film. See Section 10 for more discussion on rework and repair.

6 RAW MATERIALS CHARACTERISTICS

6.1 Viscosity Application of shear stress to a fluid results in the continual and permanent deformation known as flow Viscosity is the resistance of a fluid to flow - its internal friction. This resistance to flow is the result of two phenomena: (1) molecular cohesion, and (2) molecular transfer from one fluid layer to another, thereby developing a tangential or shear stress. Molecular cohesion dominates in liquids, and since molecular cohesion decreases with increasing temperature, viscosity does likewise. The viscosity's temperature sensitivity strongly depends on the fluid chemistry. Dynamic viscosity, μ is the ratio of the shearing stress to the rate of deformation. The common units of dynamic viscosity are the Pascal•second (Pa•s) or centipoise (cP; 1 cP = 1 mPa•s). Kinematic viscosity (υ) of a fluid is its dynamic viscosity divided by its density, or $\upsilon = \mu/\rho$. The common unit for kinematic viscosity is the stoke (St), but the centistoke (cSt, 1/100 stoke) is commonly used for convenience. For simple, low viscosity liq uids (Newtonian) the viscosity does not depend on the shear rate. However, for non Newtonian fluids (e.g., conformal coating,) viscosity decreases as the shear rate increases; this phenomenon is known as 'shear thinning.'

Commercial viscometers, such as those described in paragraphs 7.1.1 and 7.1.2, below, are simple instruments which measure flow resistance at an undetermined, or undefined, shear rate. Data generated with these instruments strongly depend on the test conditions and therefore should be quoted with the test results Comparison of data generated with other viscometers is not recommended.

Control of viscosity is of utmost importance when automated spray type conformal coating machines are used. Too thin a coating (lower viscosity) may cause conformal coating to migrate up between the outside diameter of electrical contacts and the molded body of sockets and connectors, ultimately resulting in the coating being deposited on the inside of electrical contact sockets.

6.1.1 Spindle Measurements Brookfield-style viscometers estimate a fluid's dynamic viscosity with a rotating disk or T-shaped spindle. The disc or spindle type, rotation speed, and specimen temperature should be reported when quoting data generated with these instruments.

6.2 Viscosity vs. Rheology There are essentially two methods to determine the suitability of the coating for application: either viscosity or rheology. Rheology uses 'flow cups' to estimate a fluid's kinematic viscosity by measuring the time required for gravity flow through a calibrated orifice (e.g., Ford, Zahn, etc.) It is not practical to attempt a correlation of viscosity to the rheology of a product. They are two fundamentally different measurement techniques.

6.2.2 Flow Cup Measurements Flow cup viscometers estimate a fluid's kinematic viscosity by measuring the time required for gravity flow through a calibrated orifice. The specimen density and temperature should be reported when quoting data generated with these instruments

Dynamic Viscosity (cP) – Kinematic Viscosity (cSt) x Specific Gravity of liquid

The accuracy of flow cup measurements is approximately ± 20%. Data generated with this instrument is strongly operator-dependent. To minimize such dependency the technique defined below is suggested.

Immerse the flow cup in the liquid. Have the stopwatch in your hand as you lift the flow cup from the liquid with the other hand. Start the clock when the top of the flow cup breaks the surface of the liquid. Lift the cup quickly from the liquid Stop the clock when the flow ceases to be continuous and steady.

There are many flow cup viscosity measurement standards See Appendix B for details.

6.3 Effect of Temperature Generally speaking the warmer a liquid gets the lower its viscosity and rheology becomes. Some materials are far more sensitive than others are, but for good comparison of data the temperature at which the measurement is taken should be recorded. 25°C [77°F] is a common standard.

A temperature compensation chart can be made for a specific 'control' material by plotting the viscosity (measured by whichever method) against temperature. Viscosity vs. temperature depends on the chemistry. Consult your material suppliers for viscosity vs. temperature profiles.

6.4 Surface Properties The surface properties of a conformal coating material play a major role in the wetting of the surfaces to be coated. If the surface tension of a coating material is too high relative to that of the surface to be coated, then the result will be de wetting or an "orange peel" effect. Surface tension and surface energy varies with the composition of the materials; not only the chemistry of the resin, but also the chemistry and quantity of thinner added. Therefore, viscosity or rheology adjustment will alter the wetting characteristic of a material on the surface to be coated.

7 COMPATIBILITY

7.1 Compatibility with Process Materials It is important when reading the following section, to recognize that all coatings seal in as well as out. To successfully apply a conformal coating to a PCA, compatibility of the coating with various materials on the PCA during the application and curing processes need to be considered. This includes compatibility with board or component surfaces, solder masks, common contaminants such as flux residues, and chemicals such as plasticizer, defoamer, and mold release agent.

7.1.1 Solder Masks The terms "Solder Resist" and "Solder Mask" are frequently used when referring to any type of permanent or temporary polymeric resist coating material. The term "solder resist" is used in this document as a general term when referring to any type of permanent polymer coating materials used on PCB. Solder resists are used to limit and control the application of solder to selected areas of the PCB during assembly soldering operations. Solder resist are also used to control and limit surface contamination of printed board surfaces during soldering and subsequent processing operations. See IPC 6012 and IPC-SM-840 for solder resist application and material qualification requirements.

Compatibility of the solder mask and substrate with the conformal coating of choice is essential to produce a high quality PCA The large number of solder mask, substrate, and conformal coating combinations make a detailed list here impractical. The end-users should discuss the compatibility criteria of the conformal coating with the conformal coating supplier. Qualification of a given system including solder mask, coating materials and process parameters should be completed prior to the implementation of these materials.

Solder resist materials are not intended for use as a substitute for conformal coatings that are applied after assembly to cover components, component lead/terminations and solder connections. Determination of compatibility of solder resist materials with conformal coating materials, or other substances, is dependent upon the end item assembly environments.

The types of solder resist include:

- Deposited image, (liquid) screen printed form.
- Deposited image, prepunched film.
- Photo defined image, (liquid) resist form.
- Photo defined image, (dry film) resist form.
- Photo defined image, temporary resist.
- Photo defined image, dry film over liquid.

NOTE: Touch up, if required to cover these areas with solder resist, should be of a material that is compatible to and of equal resistance to soldering and cleaning and compatible with the conformal coating as the originally applied resist.

Certain methods of solder mask application would affect the adhesion performance. See 7.3 for more information on adhesion. Depending on how solder masks are applied, compositions may be different: e.g , curtain-coated application may require a defoamer whereas screen-printed application may not.

7.1.2 Flux Residues Flux is used in the soldering process to promote solder wetting. Fluxes can be generalized to three basic groups: high solids rosin fluxes (e.g., a solids content above 15%); water-soluble or OA fluxes; and no-clean and low residue fluxes. To learn more about fluxes, see J-STD-004 and IPC-HDBK-001.

Fluxes leave residues In general, high solids rosins and water-soluble fluxes are more aggressive in nature, and are thus more often subjected to cleaning processes prior to conformal coating The high solids rosins are cleaned using solvent, aqueous, or semi-aqueous processes Water-soluble and OA fluxes are most often cleaned using aqueous-based or pure aqueous cleaning regimes. The degree to which these often corrosive residues are removed may greatly impact the reliability of the manufactured hardware. Poor cleaning may lead to electrochemical failure mechanisms, such as current leakage, corrosion, and metal migration or dendritic growth.

The adhesion of conformal coatings to the hardware surfaces can also depend on the completeness of cleaning. A high solids rosin flux, if not cleaned well, can leave high levels of residual rosin, which may impact adhesion, although most coatings adhere fairly well to rosin. A water soluble flux may contain high molecular weight surfactant elements (which makes the flux soluble by water) These surfactant agents, such as polyglycols, are hydrophilic (water attracting) and may adversely affect adhesion. Thorough cleaning should remove both the corrosive ionic elements as well as the nonionic organic elements. No-clean fluxes may contribute to decreased adhesion if they are over-applied.

Low residue fluxes are benign in nature and are intended for use with a no-clean assembly process. As such, the flux residues remain on the hardware, often functioning as an intermediate layer between the hardware and the conformal coating. The amount of flux residue remaining is a function of the solids content of the flux (most are 1-5% solids), the preheat dynamics (hotter means less residue); and the reflow environment (air or nitrogen)

Bonding between a conformal coating and a low residue flux layer may be problematic. Some flux residues are designed to remain soft for in-circuit test probes Others cure to a hard, glossy shell Flux residues which leave a hard, glossy residue layer are often more difficult to bond to Flux residues which leave a matte or dull finish may bond better to conformal coatings.

For cleanliness assessment techniques, refer to 8 1.2. Guidelines and requirements on cleanliness levels can be found in IPC-HDBK-001 and J-STD-001.

7.1.3 Cleaning Media Post solder cleaning and drying procedures may leave residues of contaminants and/or cleaning media on PCAs to be coated Compatibility with cleaning media, either solvent or aqueous media, need to be verified. Incompatible cleaning media may lead to poor wetting of the coating during application, inhibition of cure, poor adhesion of the cured coating, or long-term reliability problems of the coating.

7.1.4 Plasticizer Plasticizers are materials added to plastics and/or elastomers to increase flexibility. The amount may vary depending on the desired final properties of the material to which it is added Plasticizers are mobile fluids within a plastic and as so, migrate to the surface The presence of plasticizers can potentially lead to compatibility issues such as lack of adhesion, inhibition or migration to undesired areas of the PCB. Refer to 8.2 and 8.3 for details on inhibition and adhesion. Plasticizers may also migrate to the cured coating and cause swelling and lifting which are detrimental to coating performance.

7.1.5 Defoamer Defoamer is an additive to prevent gassing, bubbling and foaming during application. Defoamers are sometimes used in potting materials, curtain coated solder resists, etc.

7.1.6 Mold Release Agent Mold release agents are typically used during manufacturing of plastic components. These mold release agents can inhibit the adhesion or the cure of conformal coatings. This can be observed as delamination on a component.

7.1.7 Marking Many of the circuit card assemblies have markings used to identify components, subassemblies and reference designators for component placement and orientation. Examples of markings include, but are not limited to, marking inks, stamping, impression stamping, engraving, silk screening, etc. As such, these markings, as with other PCA features, also need to be coated for protection against extreme environmental exposures. However, markings have the additional requirement in that the conformal coating selected and applied should not change or affect its legibility, particularly after exposure to environmental life cycles. Examples of conformal coating compatibility with markings may include but are not limited to discoloration, adhesion, index of refraction, and clarity

7.1.8 Temporary Masking Compatibility should always be verified between the masking material and the coating material. Some masking materials contain a substance that is incompatible with the coating materials. For example, natural latex liquid mask contains alkaline which inhibits the cure of certain catalytic conformal coating products.

Temporary masks usually leave some form of residue. It is important to evaluate whether this residue can be harmful

to your process before implementation An example of this would be tape residue left from the masking process during gold plating of contact points on the PCB.

To have a consistent and good quality coat, it is imperative that the PCB assembly to be coated is cleaned.

Residues that could impact the coating.

- Adhesives.
- Hand or skin care products.
- Human agents - perspiration, acids and/or oils.
- Mold release agents.
- Oils - mechanical and/or human.
- Others depending on the process your supplier is using and the process you are using.
- Silicones.
- Some surfactants.

It is suggested that preproduction products be processed prior to the validation of actual production.

See 8.3 for more information on masking materials and masking processes.

7.2 Inhibition Inhibition is defined as the inability for the coating materials to obtain the desired properties at the manufacturers' specified time and temperature. This is an issue only with solvent-free formulations

Inhibition is caused by the contamination of the catalyst in heat-cure (addition-cure) conformal coatings with trace quantities of certain types of chemicals These chemicals interfere with the cure reaction and thus prevent conversion of the material to the desired solid. Extremely small quantities of inhibitors may be sufficient to produce this effect.

There are certain situations, however, where the cure reaction cannot proceed normally. These conditions occur when materials called inhibitors are present. In the presence of such an inhibitor, the cure in the immediate vicinity of the inhibiting material is poor. In this inhibited area the conformal coating remains in its liquid state even though the cure schedule has been completed. This liquid material remains liquid regardless of any subsequent attempts to convert it to a solid.

Coatings that cure by a free radical mechanism may be subject to inhibition. Coating formulations that derive their free radicals from UV photoinitiators or organic peroxides are examples. In the presence of atmospheric oxygen, reactive radicals react preferentially with oxygen to form inactive, nonpropagating, alkyl peroxy radicals. The most common signs of oxygen inhibition are a tacky surface or uncured material on the surface after cure. Increasing the UV intensity and/or cure temperature usually solves the problem. With proper cure conditions, reactive radicals form much faster than oxygen can diffuse into the thin film, and complete cure occurs. Alternatively, curing under an inert gas eliminates oxygen inhibition.

7.2.1 Types of Inhibition

7.2.1.1 Interfacial Inhibition Interfacial inhibition occurs at the interface between the substrate and the coating This is the most difficult type of inhibition to detect. It is most often diagnosed as an adhesion problem rather than a compatibility mismatch. Interfacial inhibition can be remedied by cleaning the surface of the substrate, baking out the substrate to flash off volatiles or applying a barrier coating, e.g., primer and changing the cure system.

7.2.1.2 Mild Inhibition Mild inhibition is most often observed when the conformal coating takes longer to cure than what the material supplier has stated the cure time to be on the Technical Data Sheet. Most cases of inhibition can be overcome by cleaning the surface of the substrate, baking out the substrate to flash off volatiles, heat accelerating the cure, applying a barrier coating, e.g., primer, or by the addition of cure accelerator

7.2.1.3 Gross Inhibition Gross inhibition exists when the inhibited area remains in its liquid state even though the cure schedule has been completed. Options for overcoming gross inhibition include changing the substrate or selecting a nonaddition cure conformal coating, e.g., moisture cure conformal coating.

7.2.2 Location of Inhibition Inhibition sometimes occurs on the exposed surface while it is curing in a contaminated oven In these cases, the atmosphere within the oven contains sufficient curing agent or catalyst leftover from a previous product to cause inhibition of the surface of the heat-cure conformal coating. Solutions to this problem are to heat the oven at its maximum temperature for eight hours to remove residual volatile inhibiting materials or use a dedicated oven.

Residuals left on the PCA are another potential source of inhibition. In most cases it is not the material from which the substrate is made that has caused the inhibition. But rather, residuals left from other materials that have been processed on the PCA or from residual oils remaining on the substrate surface such as greases, mold release agents, or hand lotions.

These same considerations apply to other tools used in the processing of the conformal coating. Equipment such as funnels, dispense tubes, hoses, seals and gaskets sometimes pick up and retain residuals. They should be scrupulously cleaned or replaced before being used with heat-cure conformal coatings.

7.2.3 Causes of Inhibition The most common causes of inhibition are sulfur or sulfur-containing chemical compounds, amines and certain other nitrogen-containing

chemical compounds, acidic materials (usually organic acids) and organotin RTV silicone rubber catalysts. Exceptions to sulfur or nitrogen compounds that inhibit heat-cure conformal coatings are certain flexible polyurethanes They are commonly contained in some gloves, finger cots, masks, sleeving, solder masks, certain fluxes, mold release agents, process hoses, gaskets, O-rings and other rubber products, hand cream, uncured epoxy and urethane. For details on potentially inhibiting compounds, see 7.2.4 Compatibility Check List.

As stated before, organic acids are inhibitors The reaction byproduct of the peroxide catalyst in many heat-vulcanized rubber stocks is an organic acid. Thus, if the rubber has not been properly post-cured, it is possible that acid can remain and cause inhibition This problem is particularly acute with hot-air-vulcanizable silicone rubber because the acid formed during its vulcanization has a much lower volatility than the acid byproducts of other silicone rubbers. As a consequence, longer post-cures are needed with hot-air-vulcanizable silicone rubber

7.2.4 Compatibility Check List The materials and components in the following list were evaluated using a heat-curing product. It is believed that other heat-cure conformal coatings act similarly. The user should verify the compatibility of coating/board combinations prior to the final selection of the coating. The following is an example list of substances that could potentially cause inhibition with heat cure materials.

- Polyvinylchloride, plasticized.
- Epoxy, amine-cured.
- Polysulfide MIL-S-8516.
- Cellophane tape.
- Masking tape.
- Vinyl electric tape.
- Latex vacuum tubing.
- Hot-air-vulcanizable silicone rubber.
- Neoprene rubber.
- Buna N rubber.
- GRS rubber.
- Natural rubber.
- Acid core solder flux.
- Rosin core solder flux.
- Sulfur compounds such as: Thiols, Sulfides, Sulfates, Sulfites, Thioreas.
- Nitrogen compounds such as: Amines, Amides, Imides, Azides.

7.3 Adhesion Several factors affect the ability of a conformal coating to adhere to a PCA. These factors include but are not limited to.

- Cleanliness.
- Compatibility between the coating and other interface materials.
- Degree of cure.

Adhesion properties are important to the final product appearance and function. A conformal coating that does not adhere completely to the PCA is not protecting that PCA. Improper adhesion can lead to blistering, peeling, cracking, and mealing of the conformal coating, especially during thermal cycling and heat/humidity treatment. The adhesion requirement is defined by the agreement between the applicator and the end user. The end user and applicator should determine what level of adhesion produces a functional PCA and what test(s), if any, should be used to determine that sufficient adhesion has been achieved and maintained through any tests or environmental conditioning The risk for adhesion failure is not only affected by the strength of adhesion but also by the elasticity of the conformal coating A coating with high elasticity is less prone to adhesion failure when exposed to mechanical tension than a coating with low elasticity.

Adhesion of conformal coating can be tested using ASTM 3359 Method B. This test may not be applicable to certain coating types.

7.3.1 Components Poor adhesion/de-wetting of conformal coatings to component and component leads can be a problem. Usually this will be caused by the presense of silicone-based mold release agents. In some cases the problem can be remedied with a change in application method, allowing better penetration of the conformal coating in between fine-pitch leads, etc. Some components may have material on their surface that can inhibit conformal coating adhesion such as pre-pregs, heat transfer agents, mold release agents, wax, polysiloxanes (silicones) and marking inks. Component cleanliness is also an important factor in conformal coating adhesion. See 8.3.4 for discussions on cleanliness and 8.2 for discussions on inhibition.

If localized delamination occurs, it is the responsibility of the users to determine acceptability

7.3.2 Surface Finishes One of the areas on a PCA that a conformal coating has to adhere to is the surface finish of the PCB. Surface finish is the material on metallized areas of the exterior PCB layer. Previous generations of these areas on a PCB were the remaining copper after etching and other PCB processing prior to reflowing tin/lead (Sn/Pb). Newer technologies have resulted in alternate materials to Sn/Pb being used as the finish on the PCB prior to assembly processing. These materials include, but are not limited to, bare copper, immersion tin, immersion silver, immersion gold, electrolytic or electroless nickel combined with gold and/or palladium, organic solderability preservative (OSP), and other similar types of alloys. If these materials are on areas of the PCB where a solder joint is

formed, then the processing usually modifies these finish materials. Most of these modifications are the conventional assembly processing using hot air Sn63/Pb37 eutectic solder leveling or reflow methods. However, because the surface finish may contain a different metal or organic material prior to assembly processing, the resulting intermetallic in the solder joint may contain trace elements of the board surface finish. It is this type of condition and other areas of the PCB with finishes not changed by assembly processing that need to be evaluated for conformal coating compatibility. In many cases, these conditions may necessitate conducting a qualification test using a representative PCB sample before approving the intended conformal coating as "acceptable for use."

7.3.3 Cleanliness Conformal coatings seal in as well as out. The single most common deterrent to conformal coating adhesion is surface contamination. The presence of ionic residues, oily materials, and particulates on board surfaces and components can result in corrosion, insulation breakdown, poor adhesion and subsequently, failure of the conformal coating. Ionic contamination may cause mealing or vesication of the conformal coating. Oily materials and particulates do not allow most conformal coatings to adhere to the surface/substrate leading to peeling. A thorough cleaning and drying process is the best method available to minimize the adhesion problems due to residues. Even when using low-residue fluxes/no-clean processes it is very important that the assemblies do not exhibit any of the flux residues. Small traces of flux residues left on the PCA due to improper cleaning and volatilization of the flux chemistries can lead to poor adhesion of the conformal coating. The cleaning process is also a factor. When using alternative cleaning methods and chemistries, such as hydrocarbons, terpenes, esters, etc. caution should be observed with respect to residual solvents. These residual solvents can cause outgassing at elevated temperatures resulting in adhesion problems such as blisters and vesication. When using aqueous cleaning methodologies proper drying is essential. Conformal coatings may have poor adhesion due to the presence of any residual water on a PCA. See 8.1 for cleaning and cleanliness assessment methods.

For cleanliness consideration in rework and repair applications, see Section 10.

7.4 Interlayer Adhesion The degree of adhesion between layers and the degree of wetting on previously applied layer is dependent on the type of chemistry and material selected. Some chemistry needs to be cured completely before the next layer is applied whereas some chemistry would not adhere to itself while wet. It is not a common practice to utilize surface treatments between layers for a multilayer coating process; however, in unique cases, they have been used.

The user should also keep in mind the recommended coating thickness requirements. Multiple application of some materials may increase the total film build dramatically because more material may be needed to wet the surface of the previously applied layer.

For rework and repair, when a new layer of coating is applied over an old layer, the degree of wetting and adhesion may be influenced by the relative surface tension, the condition (cleanliness, wear and tear) of the old layer, and the compatibility with the coating removal method (residues of stripping agent, thermal degraded coating, abraded surface, etc). Adhesion promoters or surface treatments may be used to enhance adhesion. See Section 10 for details on rework and repair. Defining the process for recoating should be considered as part of the coating process.

7.5 Methods of Assessing Compatibility There are literally thousands of ways that you could go about either defining materials compatibility or testing the compatibility between any set of materials and the processing environment. Such an assessment becomes more focused if we concentrate only on assessing the ability of the processed hardware and conformal coating combination to achieve desired performance.

There are four basic questions to be answered in assessing coating performance:

1. *Does the coating adhere reliably to the substrate?*
2. *Does the coating limit the electrical performance of the hardware?*

   This may relate to increased rise times, propagation delays, cross-talk, etc.
3. *Does the coating protect the hardware from the end-use environment?*

   Depending on the end-use environment, the coating may be called upon to provide both a mechanical, chemical and/or moisture barrier. See Section 11 for examples on end use environment.
4. *Do the thermal expansion properties of the coating compromise the hardware?*

   In some cases, the coating has not been selected to match the thermal characteristics of the end-use environment. If the coating is too rigid and the substrate thermally expands or contracts, then the coating may crack and crumble. If the coating expands or contracts too much, it may break solder joints or fragile components such as glass bodied diodes.

Questions 1 and 4 can usually be addressed by "exercising" the coating in an environment of changing thermal conditions, such as temperature-humidity cycling. MIL-STD-202, Method 106, and IPC Methods 2.6.3.1 are examples of cyclical temperature-humidity environments

commonly used to test the adhesion of a coating to a substrate. If the end-use environment has a severe vibration environment, then vibration testing may also be needed to test adhesion and thermal expansion Such testing is commonly referred to as "shake and bake."

Question 2 can be answered by full functional tests of the hardware before and after (sometimes during) such temperature-humidity-vibration testing. If there are no electrical failures as a result of such an exposure, then the coating is probably compatible

There are a variety of ways to approach answering question 3 Most test methods simply take the coated hardware and expose it to the environment in question. The environments may consist of one or more of the following:

- Ozone.
- Mixed flowing gasses.
- Industrial pollutants.
- Salt air
- Temperature extremes.
- Humidity conditions.

If the hardware can withstand an exposure to such environments, without degradation of the coating properties, degradation of the electrical properties, or corrosion of the hardware under the coating, then that coating would be considered acceptable.

Whenever the assessment of performance is considered, an appropriate choice of test vehicle should be defined; test coupons, test boards, actual hardware, etc.

Advantages of Test Boards

- The boards are readily available in a variety of metallizations
- Standard values for acceptability are established by IPC-CC-830 Qualification and Performance of Electrical Insulation Compounds for Printed Board Assemblies (conformal coating)
- Very easy to process - good for screening experiments

Disadvantages of Test Boards

- Flat surfaces do not give the coating challenges (uniformity) represented by hardware (varying thickness)
- Flat surfaces with no through-holes do not represent the same cure dynamics as actual hardware
- Vibration testing on test boards could behave differently from final product board
- It is recommended that designed experiments be run on test boards, with a final verification run on actual hardware.

8 PROCESSING

Appendix C provides a quick troubleshooting guide for the processing of conformal coating. Specific troubleshooting instructions should be obtained from the coating manufacturers or coating applicators

8.1 Cleanliness Failure in cleaning process may leave undesired residues on the surfaces to be coated as discussed in 7.3.4.

8.1.1 Cleaning Depending on the type of fluxes used in the soldering process, cleaning of post-solder assemblies could be carried out with various systems. Figure 8-1 shows a wide range of cleaning solutions available for each type of commonly used flux.

Guidelines on cleaning solutions could be found in the following IPC documents:

IPC-SC-60 Post Solder Solvent Cleaning Handbook

IPC-SA-61 Post Solder Semiaqueous Cleaning Handbook

IPC-AC-62 Post Solder Aqueous Cleaning Handbook

IPC-CH-65 Guidelines for Cleaning of Printed Boards and Assemblies

8.1.2 Cleanliness Assessment Techniques There are numerous ways to define cleanliness and different methods of measuring the residues present on electronic hardware Which method is chosen depends on whether you are looking for ionic residues or nonionic residues.

For organic contaminants, IPC-TM-650, Test Method 2.3.38, may be used This is a visual examination of organic contaminant dissolved in acetonitrile running off the test surface. A sophisticated method is to analyze the dissolved contaminant using infrared or Fourier Transform infrared spectroscopy as outlined in IPC-TM-650, Test Method 2.3.39

For rosin flux residues, IPC-TM-650, Test Method 2.3.27, may be used This test method utilizes UV-Vis Spectroscopy to detect the presence of rosin residues in an extract solution. A more precise method based on the fluorescence nature of organic materials is the high performance liquid chromatography (HPLC) method. This cleanliness assessment technique, as outlined in IPC-TM-650, Test Method 2.3.27.1, detects specific organic species and their amounts.

For ionic residues, IPC-TM-650, Test Method 2.3.25, and Test Method 2.3.25.1, may be used. These tests detect the presence of ionizable surface contaminant by measuring the resistivity of solvent extract (ROSE). They are common cleanliness assessment techniques that may be used as process control tools. These methods do not analyze the type of ionic contaminant. If the ionic residues need to be analyzed and quantified, an ion chromatography method like IPC TM-650, Test Method 2.3.28, may be used.

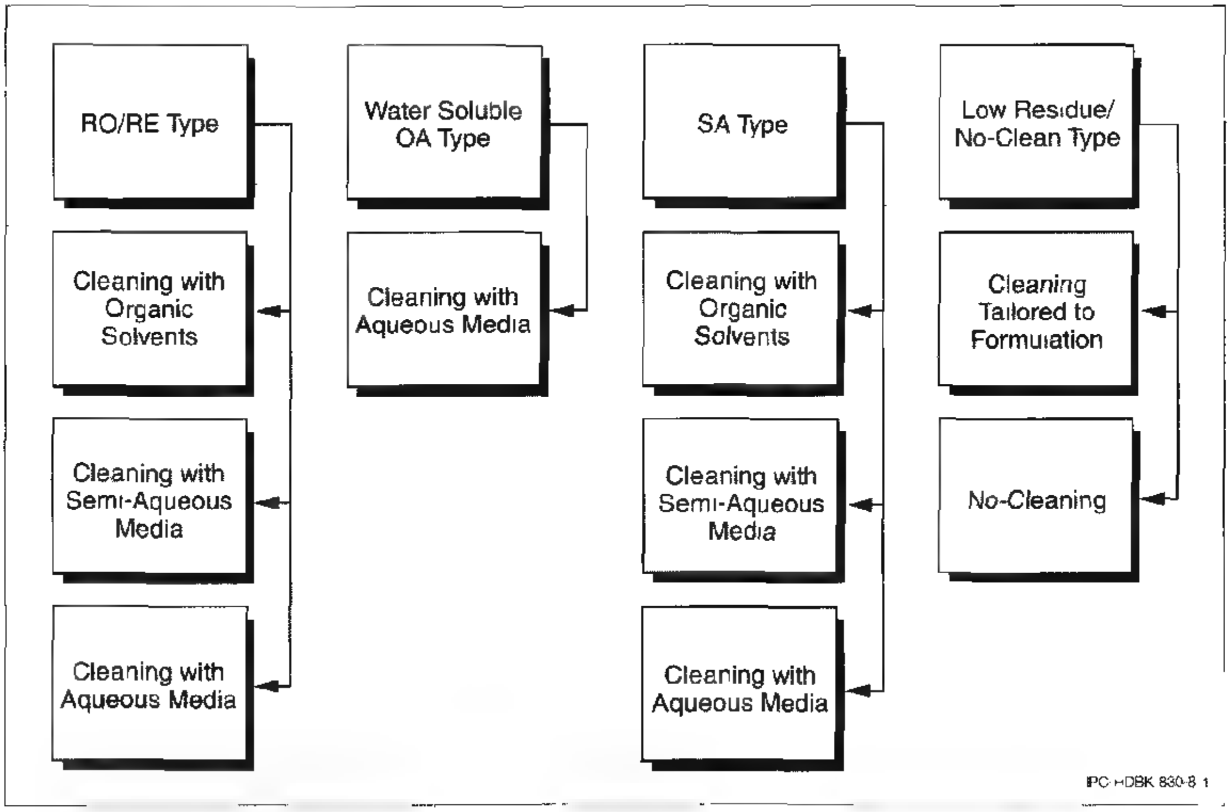

Figure 8-1 Options of Cleaning Systems According to Flux Type

Surface insulation resistance (SIR) testing may also be used for cleanliness assessment; it characterizes the effects of residues on some of the electrical properties of the test substrate. There are a variety of different test protocols, each involving accelerated aging from different temperatures, levels of humidity, and applied voltages. An example is IPC-TM-650, Test Method 2.6.3.

See IPC-HDBK-001 for a good examination of the different cleanliness assessment methods listed above, addressing both ionic and nonionic, in-situ tests and extraction-based tests.

Each of these test methods may yield some measure of the residues present, but the issue often remains of determining how much of any particular residue can be tolerated before adverse effects can be expected. Considering the variety of electronic hardware configurations, it is impossible to select a single cleanliness criteria or cleanliness assessment technique which covers all configurations. The IPC, in its assembly and joining related specifications, has taken the position that it is the responsibility of the assembler or OEM to make this determination for their hardware.

8.1.3 Processing Environment It is suggested that conformal coatings be applied in a temperature and humidity controlled environment. Problems may occur when RH exceeds 60% during the application process. This may not apply to moisture cure or water-based coatings. When curing a coating, the user should be aware of the manufacturer's recommended curing conditions. Applying coating outside of these conditions may result in coating properties, that may not be adequate to the end-use application.

8.2 Substrate Preparation The preparation of the PCA prior to conformal coating is very critical to good wetting, adhesion and subsequent reliability of the PCA. The level and type of soldering residues, handling residues, ionic residues and component mold release agents all play key roles in the success achieved with any coating and/or coating process. The solder mask also has a great impact on how well the adhesion performance of a particular coating material is

With the advent of many low residue flux chemistries, (also known as no-clean), cleaning the PCA prior to conformal coating is not desirable but sometimes is still necessary. The level of visible and nonvisible residues varies on the type of PCA, physical mass of the components and the solder excursion profile. Base line ionic and corrosive species measurement and periodic confirmation are still recommended and should be within the IPC prescribed limits. Most low residue fluxes may turn "white" after solvent extraction testing for NaCl, as a result of the alcohol in the test solution drying and developing the clear/invisible residues into a white powder. This is an esthetics issue leading

many assemblers not to test at all The adhesion of conformal coating to these residues is generally very good with all conformal coatings But, how well the residues are adhered to the solder joints should be considered, to reduce the potential for delamination of the cured coating material to the solder joint areas during the life cycle of the PCA. Numerous white powder residues have been identified. If these are detected, it may be important to have them analyzed to ensure that they are not likely to compromise the coating reliability.

Water-soluble flux processes require water washing and are generally good candidates for conformal coating because the assemblies are cleaned of many process residues. The critical factor to consider with this type of process is that the PCAs are completely dry, prior to conformal coating.

Vapor degreasing techniques prior to conformal coating operations have been outlawed in many countries due to environmental concerns. The cleanliness of the PCA should still be monitored to insure performance and reliability of the coating materials used. Compatibility of the coating with these process residues should be checked.

8.2.1 Priming Prior to coating, substrates are typically cleaned to ensure reliability and the best adhesion. To further enhance adhesion, priming or adhesion promotion is a sometimes used technique after cleaning.

8.2.1.1 Priming for Silicones To obtain optimal adhesion performance of a silicone conformal coating, a priming step may be required. Optimal adhesion is normally obtained when only a very thin, uniform coat of primer is applied.

Three steps should be considered if priming is required:

1. *Preparing the surface* - to provide a clean, dry and in some cases reactive surface.
2. *Applying the primer* – to provide a very thin and uniform surface coating.
3. *Curing the primer* to provide the ideal bonding surface for the silicone.

Optimal adhesion is obtained only when the maximum surface area and surface reactivity are made available at the time of primer application. Organic and water-soluble contaminants and loose particulates can reduce the effective surface area available for bonding. Good adhesion can only be obtained when the substrate surface is strong enough to hold a bond.

The primer should evenly coat all available surface area to achieve optimal adhesion. Some surfaces may cause a primer to bead up. Poor surface wet out like this can result in only spotty/localized adhesion. If the primer beads up when applied, solvents or other additives can be added to the primer to improve wet out. Consult the primer supplier for selection of such additives.

There is a common misconception that can cause considerable problems in the application of a primer, in nearly all cases "more" is definitely not better. Less is best. The best primer performance may be obtained with a cured primer thickness of 0.1 µm to 10 µm [3.9×10^{-3} mil to 0.394 mil], with optimal adhesion at about 1 µm [0.039 mil] coverage. Often, this thin application can be best accomplished by wiping the primer on and then immediately wiping it right back off. When applying a primer by dipping or spraying, dilution may be recommended to decrease the primer coating thickness. Over application of most primers can be evidenced not only by poor adhesion, but also by white chalkiness or flakiness on the cured primed surface. Loose material should be brushed off, however, decreased adhesion performance may still be expected.

Maximum adhesion performance is directly related to the extent of the cure of the reactive species in the primer. Primers containing silane-coupling agents begin to react with atmospheric moisture as the solvent carrier evaporates. Ideal adhesion is obtained during a "window" of extent of primer cure that will be unique to a particular adhesion system, i.e., a given surface, primer and silicone conformal coating For a given primer, the choice of silicone to be used with it usually has a greater influence on the optimal extent-of-cure window than does the choice of the surface material (Figure 8 2).

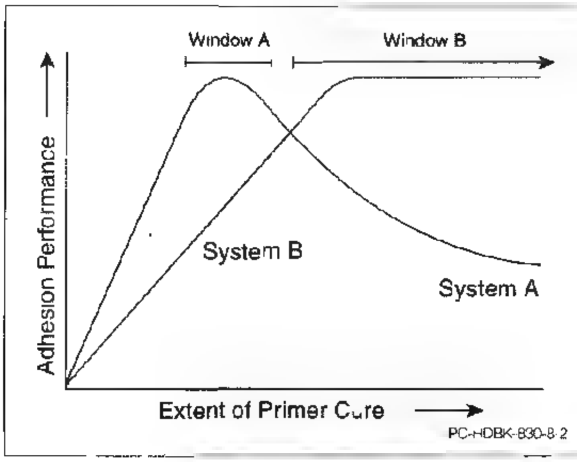

Figure 8-2 Cure Windows of Primer Cure

The extent of primer cure is controlled by three main cure conditions: temperature, relative humidity, and time (Figure 8-3). In most applications, the temperature at which the primer is cured either does not vary severely, or cannot be controlled, as is most often the case with relative humidity. The amount of time that a primer is allowed to cure, however, can usually be more carefully monitored. It is recommended that an evaluation of the effects of cure times on adhesion be carried out to maximize adhesion performance. This can be achieved by allowing the primer to cure at average or normal application conditions for 15, 30, 60,

120, and 240 minutes, and then continuing through the remainder of the normal bonding procedure. Alternatively, primers can be cured for 15 minutes at 22°C, 38°C, 52°C, and 66°C [72°F, 100°F, 125°F, and 150°F], if the normal primer cure is carried out at the elevated temperatures. Oven atmospheres can often be quite dry. This can slow the cure rate down unless precautions are taken to maintain an adequate relative humidity.

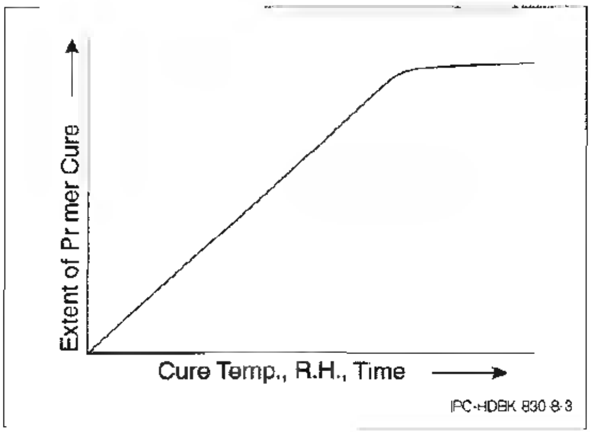

Figure 8-3 Conditions that Influence the Extent of Primer Cure

To increase the relative humidity in the primer curing area, suggestions include commercial humidifiers, open pans of water (large surface area of water) in the oven, and water misters. Water condensed directly onto surfaces to be primed degrade performance if not removed prior to the primer application.

The optimal cure time established by the above oven curing procedure is influenced by changes in temperature and humidity (Figure 8-4). Two general "rules of thumb" are:

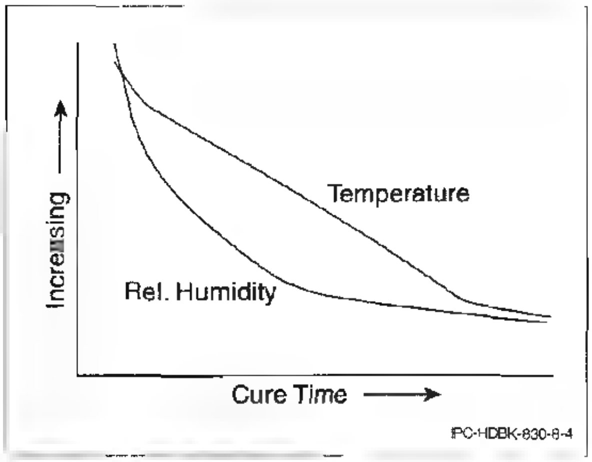

Figure 8-4 Influence of Temperature and Humidity

1. Cure may be reduced by 50% per every 11°C [20°F] increase in cure temperature given equal relative humidities (actually 18°F or 10°C = doubling of most reaction rates).
2. Cure times should be approximately doubled per every halving of the relative humidity.

There are no sure predictive means to distinguish between adhesion systems that are or are not sensitive to these conditions. Therefore, it is recommended the user determine the primer cure times at conditions that approximate the average and the extremes of the temperature and relative humidity that might be in a given application.

8.2.1.2 Priming for Acrylics No primer is known to be needed for this coating type.

8.2.1.3 Priming for Urethane No primer is known to be needed for this coating type.

8.2.1.4 Priming/Adhesion Promotion for Poly-para-xylylene (parylene) The poly-para-xylelene (parylene) chemical vapor deposition process used to coat printed PCBs usually requires an adhesion promotion step prior to deposition of the polymer. This process can be done either by gas phase deposition or a liquid immersion process. The most common adhesion promotion agent is A-174, an organosilane ester.

The vapor phase process is performed by placing the cleaned parts into the deposition chamber and promoting them by depositing an organo-silane coupling agent immediately prior to the start of the coating process. The coating equipment should be configured with this feature to perform in-chamber adhesion promotion.

The immersion process employs a dip process utilizing the organo-silane-ester coupling agent in an IPA solution. The parts are immersed for 15-30 minutes an allowed to dry. The parts are then rinsed in fresh IPA and baked out, prior to any masking, fixturing or deposition.

8.2.2 Plasma Treatment Plasma treatment is the process of placing a PCA in a vacuum chamber and using gaseous plasma to micro-etch away all exposed surfaces. Various gases are used to achieve different etch rates. This process is used as a cleaning and/or surface roughing operation. Because of the process, some areas of the PCA should be masked to prevent unwanted removal and discoloration. Selective plasma treatment may also be used. This process may not be suitable for all applications.

8.2.3 Mechanical Etching Mechanical etching is the process of bombarding a PCA with hard items (e.g., sand or ceramic pieces) to roughen up surfaces. Because of the nature of the process, some areas of the PCA should be masked to prevent damage. This process may not be suitable for all applications. This process is also known as

Micro Abrasive Etching/Removal. Users are cautioned that significant ESD damage may occur to ESDS sensitive items in event the machine used does not have built-in ESD controls, or otherwise, in the event the controls fail or the humidity drops below 30%. It is recommended that the voltage generated at the nozzle dispensing the power be verified as within an acceptable range during each daily use of the machine

8.3 Masking It is safe to say that in any application process some sort of masking material may need to be applied to an area of the PCA to be coated. Masks can include plastic boots or covers, a peelable mask, or masking tape to name a few Most masks are introduced manually by an operator, although liquid masks can be applied automatically with a dispensing robot. Maskants may leave some form of residue. It is important to evaluate whether this residue can be harmful to your process before implementation.

When masking against spraying it is often sufficient to use a 'shield' approach, which can reduce much of the time needed for masking and demasking. When the coating application method is dipping, the masking needs to be encapsulating. When masking against vacuum deposited coating, e.g., XY type coating, masking needs to be air tight and survive in a vacuum environment.

Be aware that the rear of connectors and via holes can leak coating. Conformal coatings are designed to ingress under components and will find their way into a break in masking. Often using tape and liquid masks together can be the best way to seal areas against dip coating. Create a box with the tape, then seal with the liquid mask.

Caution should be used when using liquid masks Liquid masks can flow into vias or other holes. Liquid masks are commonly used but should be allowed to dry completely before application of the coating material. Users are cautioned that liquid masking materials that subsequently harden to a rubber-like consistency may cause problems in event they are not completely removed from electrical contacts in connectors, sockets and other similar electrical interface areas.

For guidelines on the requirements of masking drawings, see 5.7. Compatibility should always be verified between the masking material and the coating material.

8.3.1 Types of Masks

8.3.1.1 Natural Latex Liquid Masks These masks are a solution of natural latex rubber in water, stabilized by an alkaline component (often ammonia). It is important to make sure that the mask is applied thin enough so that it does not remain liquid on the board for an excessive period of time, as the alkalinity can be damaging in this situation to certain substrates (e.g., Copper). Generally a thickness of less than 2-3 mm is OK.

The alkaline component of the mask can also inhibit the cure of certain catalytic conformal coating products so validation of your mask with the coating material is essential

Heating of the mask can speed up the cure, but avoid heating above 70°C to 80°C [158°F to 176°F] as this can begin to degrade the latex resulting in an effect similar to 'chewing gum.' This can make the product very hard to de-mask.

8.3.1.2 Synthetic Latex Liquid Masks These masks are a solution of a synthetic polymer in water. They are often used when natural based masks have been shown to inhibit cure of the coating used. Generally, the self-bond strength and ease of use is not comparable to natural products, but they are not necessarily as alkaline and can be lower in odor. Again, heating can speed up the cure, although excessive heat too early can cause bubbles in the mask. If solvent-based coatings are used, the solvent may react with the masking materials, and may not peel away cleanly.

8.3.1.3 Other Liquid Masks There are a variety of other masks available such as heat cure and water soluble masks. It is not recommended to use a water-soluble mask for coating masking, as they are really more suitable for the soldering process. The heat cure masks can be advantageous in terms of process time. UV curable removable acrylics can also be dispensed and cured as a mask.

8.3.1.4 Tape Masks The tape selected for masking should be nonporous to the coating material and should not produce excessive static when used Use of static adhesion tapes is not recommended when ESD sensitive components are present. Ideally, use a tape that shows a color or contrast change on contact with the substrate, this allows the detection of breaks in the masking before the board is coated (Figure 8-5). Silicon free adhesives should be employed Some tapes may deposit adhesive residues onto the assembly surfaces that may be extremely difficult to remove fully The tape should also be able to withstand the curing temperature of the coating in use

8.3.1.5 Boots, Caps, Plugs, etc. The conformal coating process requires the protection of various devices on the PCA from the coating material. These devices include electrical interconnects, test points, ground planes, and hardware to mention a few. Premolded boots and polyvinyl caps are commonly used (Figure 8-6). An advantage of boots, caps and plugs is their ability to be reused.

8.3.2 Manual vs. Automated Masking Manual masking methods typically allow the user to utilize whatever is necessary to protect an interconnect or 'keep out' area of the PCA from conformal coating. They include, but are not

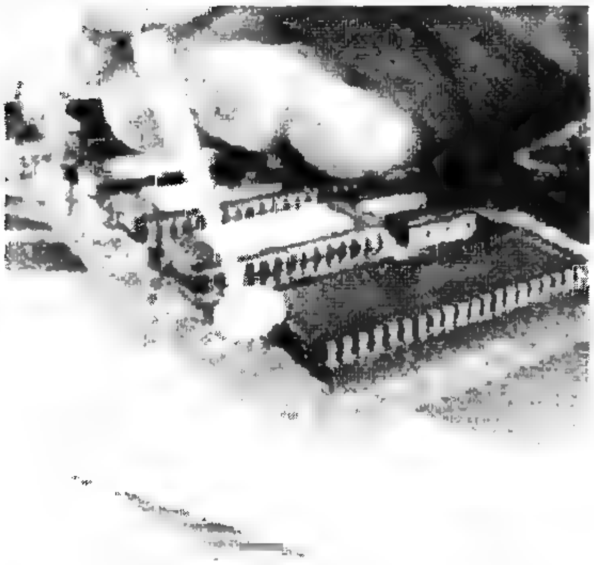

Figure 8-5 Masking Tapes

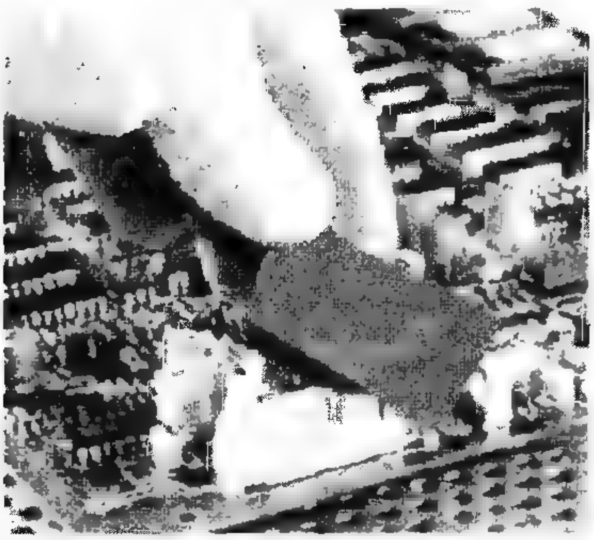

Figure 8-6 Masking Boots

limited to: molded boots, tapes, caps, plugs, tape dots, latex, UV curable removable acrylics and just about anything else that will do the job effectively.

The critical concerns are preventing leakage and easily removing them after the conformal coating has been applied and cured. All the masking media used should be removed in its entirety and should not cause any deleterious effects to the PCA.

Traditional manual methods of masking and de-masking include off-line, batch-type activities done by human manual methods. These are typically very labor intensive operations depending on the design layout and complexity of a particular board design. Masking and de-masking operations can sometimes cost more than the coating process itself.

Automated masking can include pressure/time dispensers or elaborate XYZ platforms to selectively apply the protective media to the site. Once applied, the masking media should be cured. Most require heat, ambient air or UV curing mechanisms.

8.3.3 De-masking When de-masking, caution should be observed to avoid any degradation of the coating, assembly, or board. Forms of degradation include lifting of materials from substrate, peeling, cracking, lifting of edges, physical damage to the substrate and/or components. Careful scoring may minimize degradation.

8.4 Recommended Coverage

8.4.1 Recommended Thickness

Note: IPC-CC-830 is used for qualification, qualification retention and quality conformance inspection testing purpose of the conformal coating material. For thickness requirements of applied and cured conformal coating on a test vehicle (coupon) refer to IPC-CC-830. For actual thickness requirements of applied and cured conformal coating on a printed circuit production assembly product, refer to J-STD-001 or IPC-2221.

A minimum coating thickness is required to provide the requested function of the conformal coating. This thickness depends on the type of application and the performance requirements of the end product but also on the type of coating. Insufficient thickness may result in pin holes, reduction in abrasion resistance, etc.

Typical coating thickness for an end product ranges from 0.01 mm to 0.2 mm [0.394 mil to 8.27 mil]. There is no proof that a thickness of 0.2 mm [8.27 mil] provides twice as much protection as 0.1 mm [3.94 mil]. A conformal coating applied too thick can have detrimental effects such as CTE mismatch, cracking, etc., so there is usually a maximum value of acceptable coating thickness. Solvent-based materials may experience chemical evaporation that affects the final coating thickness. For example, a coating with 50% solvents applied at film thickness of 0.2 mm [8.27 mil] will have a final cured thickness of approximately 0.1 mm [3.94].

An even thickness all over the PCA may not be easily achievable for most types of coating except poly-para-xylelene (parylene), a vacuum deposited coating. Therefore, the mean thickness of other coating types has to be increased to guarantee a certain thickness at the location where it is thinnest, e.g., at solder joints and component leads.

Since coating thickness is usually measured on a flat, unencumbered, cured surface of a PCA or a test coupon during process qualification, fulfilling the thickness requirement is no guarantee for reliable coating coverage. Therefore, the

reliability of the coated end product needs to be verified by a statistical process control with an underlying design for reliability (DfR) principle.

8.4.2 Uneven Coating Thickness Besides causing poor coverage, uneven coating thickness may increase the risk for cracking or delamination of the coating. Generally, the more rigid the coating is, the larger the risk for cracking and delamination problems, especially for products that may be exposed to low temperatures and large temperature fluctuations.

There are a number of forces that result in uneven coating thickness. The most prevalent are gravity, surface tension, and capillary reaction. Other factors that affect the variation in the thickness of the coating are properties of liquid coating material, application method, and the time to immobilize the coating after it has been applied

8.4.2.1 Gravity Gravity causes coatings to run down on vertical surfaces. This is not always detrimental. It can be used to pull coating to the end of the leads to though hole mounted components which otherwise would have very poor coverage due to the surface tension of the coating material.

8.4.2.2 Surface Tension Surface tension acts to minimize the surface area of the coating material. This is achieved by forming convex surfaces just like solder forms convex surfaces on hot air solder leveled printed boards. Thereby, the coating may be very thin on sharp points and edges such as the edges and toes of the leads to surface-mounted components.

8.4.2.3 Capillary Forces Capillary forces may cause coating material to be sucked in under packages with a low stand-off when spraying is used as the application method. This may result in a very thin coating around the periphery of component. That is, for a peripheral leaded component the coating may be thinnest at the locations where it is most important to have a good coverage. Surface tension and capillary forces may also cause formation of large fillets and bridging between leads having a negative impact on the flexibility of the leads.

8.4.2.4 Time to Immobilization The time to the immobilization of the coating after its application is an important factor in determining how much the coating migrates. By using a UV-curing material, the coating can be immobilized very quickly. A decrease of the viscosity usually results in a more even coating thickness. Contrary to UV curing, a decrease of the viscosity during heat curing especially typical for many silicone coatings, may result in a large flow of the coating material.

8.4.3 Edge and Point Coverage Gravity tends to be the biggest hindrance to successful edge and point coverage. Once applied, coatings retract from sharp points and edges on a PCA. This can cause key contact points to be exposed to the environment and inevitably produce a void in your coating process.

To offset this potential roadblock, a few options are avail able:

- A second, or thicker coating layer can be applied to the PCA to help reduce the probability of inadequate coating coverage.
- A post-coating process can include the inversion of the PCA to allow gravity to pull coating toward the end of the pin instead of away.
- A second higher viscosity coating may be utilized on critical point and edge areas to reduce the flow of material away from desired coverage areas
- The assembly may be prewarmed immediately prior to spray applications of solvent-based coatings. In this way, the solvent is more efficiently volatilized from the surface allowing improved tip and edge coverage.
- Transfer dip coating techniques may be utilized that facilitate better tip coverage as the assembly is coated inverted.

8.4.4 Application Method Automated or selective applications can coat down to 0.025 mm [1 mil] minimum in many applications, while more coverage is easily achievable, even beyond 0.20 mm [8 mil] in a single pass. Manual applications (brushing, hand spray, aerosol) can also be utilized over a wide spectrum of coating thickness, though this should be accomplished over multiple, thinner applications. Part consistency over time can be difficult to ensure in manual operations. In a dipping application, coating thickness can be greater and is highly dependent upon immersion and withdrawal speeds, coating viscosity, and solids content. A basic rule of thumb is that the slower the withdrawal speed, the thinner the coating.

When spray coating, shadowing of components may prevent that surfaces beneath them from being coated. Thus, any circuitry located beneath components may have poor protection. When area array packages are used, spraying may no longer be an acceptable application method. By using selective coating, extra coating material may be added at critical locations. Also, a second coating layer can be applied to get better coverage. Then, all sharp points and edges should have been smoothed by the first layer.

8.5 Shadowing/Bridging Bridging of conformal coating around the leads of a component has encapsulation effects on the component. The user needs to determine whether it is a desirable phenomenon according to the need of rework.

8.5.1 Accessibility Consideration The first consideration in shadowing and bridging is how accessible these

areas are on the PCA. If these contact points are not easily accessible, then it is likely that a greater volume of coating may be necessary to allow the fluid to flow into the desired coverage areas. Conversely, a higher viscosity coating can be used around critical areas where bridging may be a concern. A higher viscosity fluid will ensure greater placement integrity and a reduction in flow and creeping under components.

8.5.2 Curing Consideration Cure conditions should be considered when shadow coating or bridging is employed. This is of particular concern when a coating relies upon UV light exposure to trigger the curing process. Shadowed areas are typically inadequately exposed, thus, a proper secondary cure mechanism should be in place. If not, uncured coating may be present underneath board components.

8.5.3 Shadowing Techniques To properly apply conformal coating in a covered or shadowed area when spray coating, angle the spray head or nozzle to better focus the material under shadowed areas. This technique is most effective when a shadowed area is covered by a component with a height of 3.175 mm [125 mil] or greater from the board surface. In this instance, the atomizing air pressure helps push the coating into the shadowed area. For lower lying components or for manual operations, you may elect to flow coat the area for best shadow coverage.

Dip coating allows coating to penetrate under components. Depending on stand-off heights, the viscosity and the dip dwell time may need to be adjusted to allow air to escape from beneath the components. Vacuum deposited coating can penetrate into much smaller crevices than possible with liquids, practically eliminating shadowed areas.

8.5.4 Bridging Techniques To bridge, or coat under components, start with an initial spray over the entire component. Flow coat on one, two, or three sides over the leads similar to an underfill application. Flow coating all four sides of a component could potentially produce an air bubble underneath. After successfully flow coating up to three sides, the material may begin to wick underneath the component over a short period of time.

8.6 Viscosity Adjustment

8.6.1 Methods of Viscosity Adjustment Liquid coatings can be divided into two categories, solvent-based and solvent-free coatings. Solvent based coatings generally require the addition of thinner to adjust viscosity for the given applications. Coatings supplied solvent-free from the manufacturer should not require thinner; viscosity adjustment may be done using other methods upon consultation with the vendor.

The coating manufacturer should be able to make appropriate recommendations on the type and quantity of thinner to use for different application methods. The equipment manufacturer should also be consulted because there may be some slight differences in the dilution ratios among different equipment.

8.6.2 Objectives of Viscosity Adjustment For spraying, thinner may be necessary to eliminate cobwebbing (typically acrylics) or to eliminate bubbles when drying the coating (typically urethanes and silicones). Diluting the coating can also be a means to achieve thinner dry films.

Control of viscosity is of utmost importance when automated spray type conformal coating machines are used. Too thin a coating (lower viscosity) may cause conformal coating to migrate up between the outside diameter of electrical contacts and the molded body of sockets and connectors, ultimately resulting in the coating being deposited on the inside of electrical contact sockets.

Cobwebbing results when cure/evaporation of the solvent occurs too rapidly. There may be some equipment adjustments to eliminate this. Nevertheless, depending on the severity, additional thinner may need to be added. Should this be necessary, the solids content will have been reduced and may demand that additional coating is applied to obtain the desired cured film thickness.

Bubbles in the dry film typically appear after the parts have been cured. Adding thinner, decreasing the wet film thickness, decreasing the oven temperature, and decreasing the exposure to humidity (some urethanes and silicones react with moisture to cure) are all possible solutions.

For dipping, the thickness is controlled by the withdrawal rate and the viscosity. The viscosity of the coating can be adjusted to provide the desired thickness at the desired coating speed/withdrawal rate.

For brushing, lower viscosity improves the flow of the coating and allows thinner coats to be applied.

8.7 Application Methods Conformal coating materials can be successfully applied by a variety of different methods. For the purpose of this handbook, we will focus our attention on the most popular and successful techniques; spraying, dipping, brushing, selective coating, and vacuum deposition coating. Each of these application methods has advantages and disadvantages, as well as considerations for coating dilution, material utilization, shadowing, and layering. When selecting a conformal coating, the intended method of application needs to be considered. This will avoid inconsistencies in reliability data between test and production conditions.

8.7.1 Manual Spraying Manual spraying is commonly used when low volumes of parts need to be coated. In manual operations, aerosol cans or handheld spray guns can be utilized.

Manual spraying is very operator dependent. The operator heavily influences the quality, coverage, consistency and uniformity of the coating on the PCA. A black-light inspection to verify coverage is typically employed. Hand touch-up may be required using a brush.

8.7.1.1 Aerosol Spraying Aerosols have a low solids content (less than 5%), so ventilation of the spray area is paramount. Spray in a horizontal position to prevent flow of coating into undesirable areas, and to assist in producing a consistent film build. Masking is highly recommended. See 8.3 for more information on masking. To ensure total coverage, apply a thin coating (approximately 0.025 mm [1 mil]) during each pass, rotating the board 90° after each pass.

While initial startup costs for an aerosol application system may be low, efficiency is a concern. Material utilization for aerosol applications is typically 25% to 40%. Much coating material is generally lost due to over-spray and coating the masked areas.

8.7.1.2 Handheld Gun Spraying Handheld spray gun operations can be very similar to aerosol applications. Proper ventilation should be ensured. Again, the spray application should be completed in a horizontal position in four thin (0.025 mm [1 mil]) passes, rotating the board 90° after each pass. Masking is highly recommended. A handheld spray operation should consist of a spray gun, a material reservoir, and a cycle actuation device (trigger assembly, valve controller, etc.). Many spray gun manufacturers supply handheld spray guns that can be used effectively for manual operations (Figure 8-7). Fluid and air pressure can be regulated to produce a fine, atomized spray. When using a material reservoir be sure to pressurize your conformal coating material with dry, un-lubricated air or nitrogen. This is especially prudent for moisture cure coatings that may take on cured characteristics if exposed to unfiltered air for a prolonged period of time.

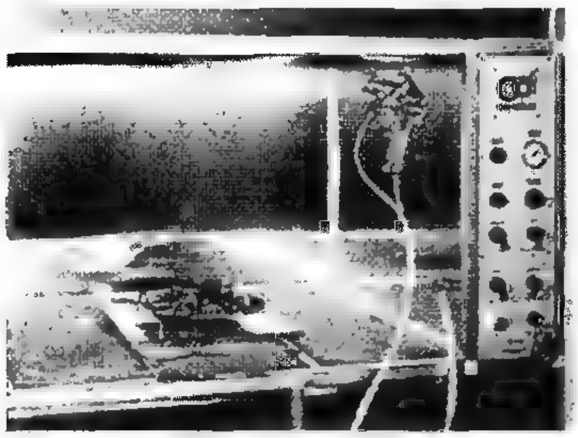

Figure 8-7 Spray Booth with a Manual Spray Gun

Care should also be given to UV-curable coatings. Due to the presence of UV in sun and light sources, steer away from using clear feed lines from the reservoir to the spray head. Black or opaque tubing can easily eliminate any concerns over UV light penetrating into and altering your coating process.

Handheld spray operations can be a quick, relatively inexpensive avenue into a conformal coating process. Spray heads can accept higher viscosity fluids than aerosols and may not require dilution. A more controlled spray process can result in greater transfer efficiencies; however, this is dependent upon time and complexity of each PCA.

For handheld spraying, an open-faced spray booth is required to contain overspray and odors. Per NFPA specifications, an airflow of 30.48 m/min [100 ft/min] should be present over the entire booth opening. This can translate into exhausting a considerable amount of conditioned air (Volume of conditioned air, in ft^3/minute = 30.48 m/min [100 ft/min] x booth opening ft^2). Especially if the booth is used to rack the wet parts and let them air dry. The booth needs to be larger and the exhaust on for extended time periods. Conditioning (temperature, humidity) make-up air can be expensive and should be considered when performing start-up costs. In aerosol or manual spray operations, and where solvent-based coatings are being employed (except water-based coatings) then it is suggested that the operator be supplied with adequate respiratory equipment.

The spray booth has filters to trap the solids and allows the vapors to pass through. These filters should be disposed of and may be considered a hazardous waste, depending on the coating being used and local regulations.

8.7.2 Automated Spraying Automated spraying is effective for spraying high volumes of parts, similar or mixed. To automate a spray process, one of two methods can be employed, a reciprocating spray system or a selective coating unit. Selective spray systems are addressed in 8.7.5.

Automated systems offer a few advantages over manual spray operations. See Figures 8-8, 8-9 and 8-10 for some examples of automated application methods. Automated systems provide increased throughput capabilities and a more uniform coating. With automated equipment, the machine controls the quality and does not require a specially trained 'painter.' Training operators and maintenance is necessary but should not require special skills beyond that of other production equipment.

However, an investment should be made into masking or shielding devices, as well as the automation equipment itself (Figures 8-11, 8-12 and 8-13). Automated equipment also requires exhaust in the spray chamber. The manufacturer specifies the exhaust requirements for the system. Some automated spray equipment is designed with ovens directly after the spray chamber. The oven is used to get

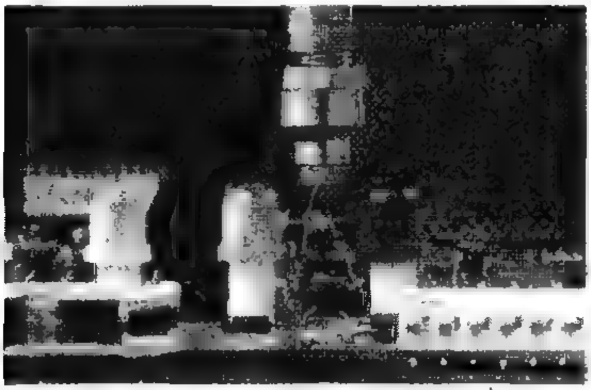

Figure 8-8 Nonatomized Curtain Coater

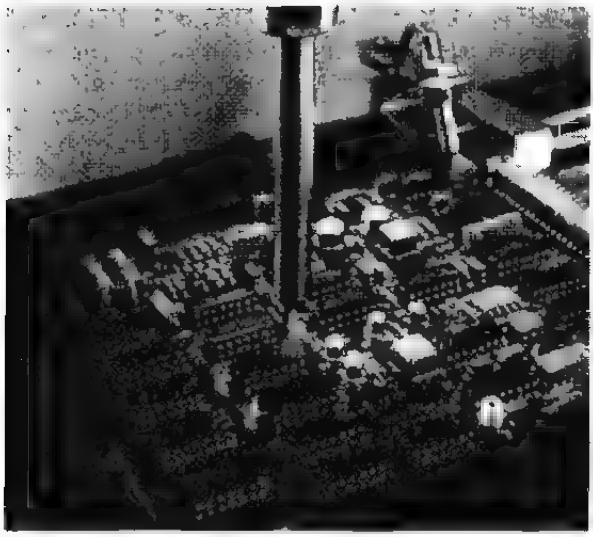

Figure 8-9 Swirl Applicator

the parts to a tack-free state. This eliminates handling parts while they are still wet. Depending on the coating, ovens should be constructed to safely handle flammable vapors if such vapors are given off during curing.

A reciprocating sprayer incorporates a paper belt conveyor that transports a masked PCA into the spray area There a bank of spray heads move back and forth over the PCAs producing an even film build. Material tanks feed each spray head in a similar fashion to the manual process described in 8.7.1 2

Although material would still be lost due to overspray and coating the masked areas, through proper system design, it is possible to have a coating transfer efficiency (TE) in the 80% range. The material utilization can be maximized by optimizing the placement of PCAs on the conveyor. Variables such as temperature, valve, air cap and nozzle design, atomization pressure, humidity and flow rate all have an

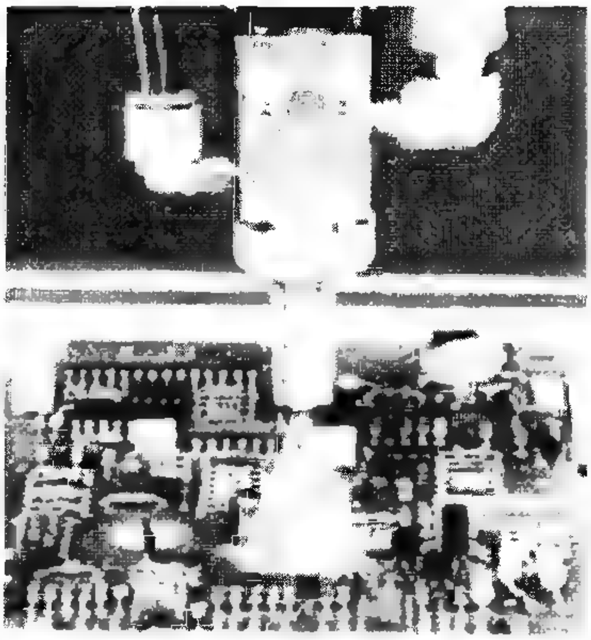

Figure 8-10 Improvements in spray technology now permit pattern widths as tight as 3.175 mm [125 mil] for work around sensitive keep-out areas

impact on the overall efficiency of the automated spraying system. Generally, viscosity for spraying is lower than for dipping.

8.7.3 Dipping Dipping is a low cost, efficient way to apply a conformal coating. This method consists of the immersion of a PCA into a bath of coating to supply coverage (Figures 8-14 and 8-15) Masking of sensitive areas is required. Assemblies should be dipped vertically, as opposed to horizontally. Coating thickness relies upon the immersion and withdrawal speeds. Typically, immersion speeds are recommended to be 152 mm to 305 mm/min [6 in to 12 in/min]. An applicable speed should be chosen to allow displacement of air surrounding all components and prevent entrapping air. Once immersed, the PCA should remain in the bath until all bubbling has ceased.

The withdrawal rate from the dipping process should be slower than the cascade effect of the coating. This can typically be 25 mm to 152 mm/min [1 in to 6 in/min]. The slower the withdrawal rate, the thinner the coating on the assembly.

Faster withdrawal rates, and lower viscosity materials may cause coating to flow and can produce an uneven coating over the PCA. This is simply a product of gravity and should be evaluated prior to implementation. Consult your material manufacturer on proven ways to prevent solvent loss and material cure within the dipping process.

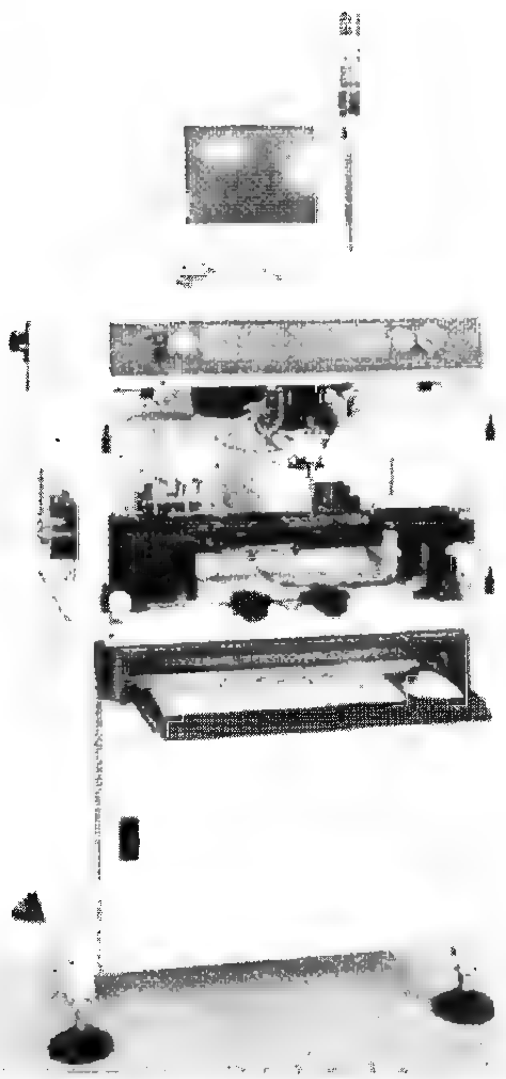

Figure 8-11 Conveyorized Applicator

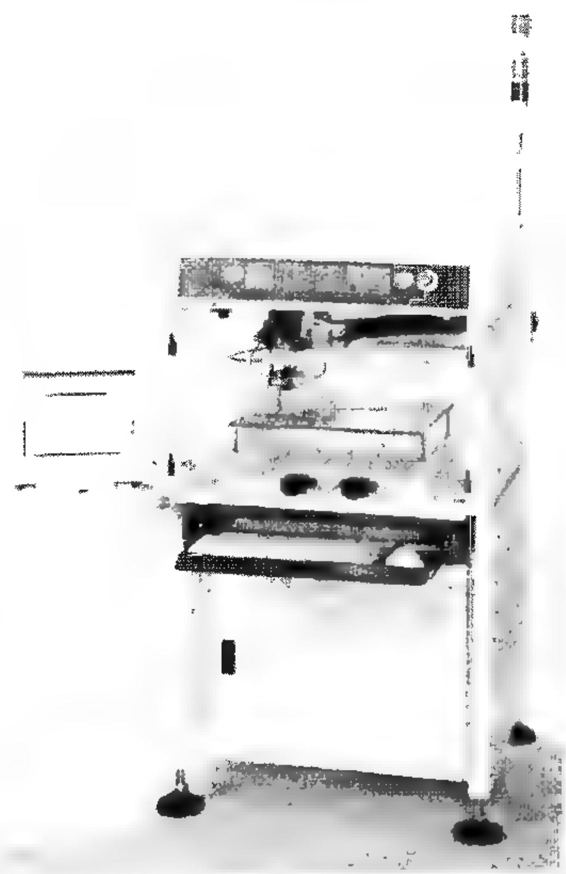

Figure 8-12 Stand-Alone Batch Applicator

Dip coating is a common choice for high volume production, as jigs or carriers may be employed that permit as many as 40 PCAs to be coated every cycle. This commonly equates to around 500 PWAs per hour However, care must be taken to eliminate the need for masking. That can be done through design by locating components that should not be coated onto one edge of the assembly.

8.7.4 Brushing To coat a limited quantity of PCAs, a brushing technique may be utilized. This is a labor-intensive operation that may not be suitable for high production rates. This application method consists of manually using a brush or similar device to 'paint' the coating onto a PCA. This can reduce some masking due to the controlled nature of the process. Brushing is most often used in a repair or touch-up mode. Obtaining uniform film builds over an entire PCA is difficult in this method.

Be wary of air bubbles forming during the application process. Flow rather than paint to reduce the possibility of air introduction. It may be necessary to restrict to only one or two strokes of the brush to reduce the possibility of air introduction

Considerations should also be given to moisture cure coatings that may change in viscosity during application. Use an appropriate solvent or cleaning agent to remove coating from a brush that may be hardened by cured material.

8.7.5 Selective Coating Selective coating is a growing technology in the application of conformal coatings. The goal of introducing a selective method is to reduce, and ultimately eliminate masking operations on PCAs. This can significantly reduce labor costs associated with other methods. Selective coating does permit inline production and is suitable for high production volumes. Initial startup costs are higher than manual operations, however, savings can be achieved from reduced labor cost and increased material utilization

A selective coating robot can employ two, three, or four axes of programmable motion. In many cases, tilt axes are employed as an additional motion capability The greater number of axes utilized in a selective system, the greater

Figure 8-13 Automated Applicator

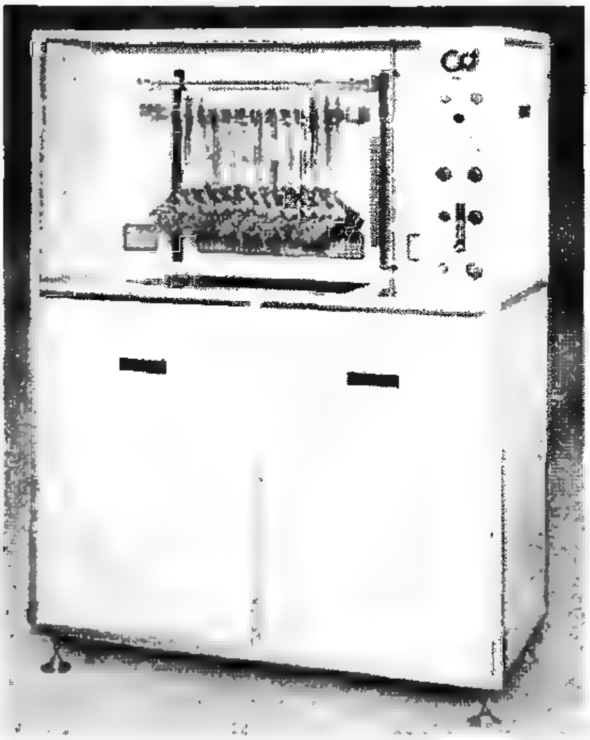

Figure 8-14 Dipping Equipment with Smaller PCAs

the flexibility, and subsequently, more PCA configurations should be able to be coated without masking. Motion in the x, y, and z-axis has been fairly standard over time. Tilt axes are pneumatic or motor controlled. This motion changes the application point of the valve from a vertical position to an angle. Tilt axes are typically on/off motions and are not programmable in nature. Four axis systems are programmable and permit acceleration and deceleration and permit ease of acceleration and deceleration. A fourth axis of motion permits 360° rotation of the entire end effector.

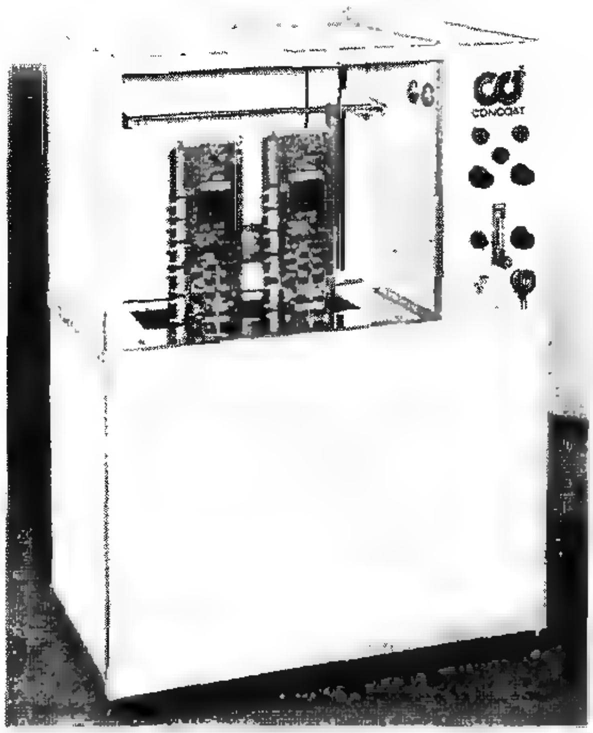

Figure 8-15 Dipping Equipment with Large PCAs

Selective applications use either an atomized mist or non-atomized curtain applicator to apply a uniform coating as thin as 0.025 mm [1 mil]. Needle valves can also be used to apply dots and beads of coating in underfill areas, or around masking zones. A material tank feeds the dispense heads and should again be pressurized with dry, unlubricated air or nitrogen.

Selective systems offer a degree of process controls not available in manual systems. For example, flow meters can give real time data on how much coating has been applied on each PCA.

8.7.6 Vacuum Deposition (XY) Poly-para-xylelene (parylene) films are deposited on a substrate in a vacuum chamber by Vapor Deposition Polymerization (VDP) (Figure 8-15). As a gaseous process, the coating is allowed to penetrate minute spaces and cover all exposed surfaces. It is used when total coverage and protection is required. No-coat areas can be masked using various methods.

Films can be accurately deposited in a thickness range from submicron to several mils. Uniformity and repeatability are high and predictable. Poly-para-xylelenes (parylenes) have very high dielectric properties, are excellent moisture and corrosion barriers, are low outgassing, and as a pure polymer, are stable over long-term

This coating process requires special vacuum equipment and trained personnel, or the use of a coating service provider

Figure 8-16 Vapor Deposition Polymerization Unit

8.8 Multi-Layering When multiple layers are required, vendors should be consulted for appropriate multi-layering techniques. Certain chemistries require complete cure before subsequent coating, while others may require partial cure. It is not a common practice to utilize surface treatments between coating layers to ensure adhesion, however in unique cases, they have been used.

The user should also keep in mind the recommended coating thickness requirements. Multi-layering of some materials may increase the total film build dramatically because more material may be needed to wet the surface of the previously applied layer.

8.9 Cure Mechanisms Depending on the chemistry of the coating, cure mechanisms can be categorized as follows. Some materials employ dual cure to ensure complete cure of all the material applied on a PCA. See Figure 4-1 for cure mechanism for each coating chemistry.

8.9.1 Room Temperature Cure Room temperature cure is a relatively slow process. The coating is cured in an ambient environment Solvent based coatings should be subjected to room temperature cure to evaporate the solvent prior to any other cure to prevent entrapped solvent (8.10.4). Some coatings may be accelerated by the application of mild heat (8.9.3) and/or humidity (8.9.5).

8.9.2 Heat Cure Heat is required to cure the coating. In general, these coatings may be faster curing than room temperature or moisture cure coatings. Some coatings should be heat cured, some may only use heat as a means of accelerating cure (8.9.3).

8.9.3 Heat Accelerable Some room temperature curing may be accelerated by the application of heat. The acceleration of moisture cure coatings may require additional humidity (8.9.5) Consult the material supplier for the specific conditions for acceleration.

8.9.4 UV Cure Most UV curable conformal coatings contain a secondary cure mechanism to cure coating material that migrates under devices that cannot absorb the UV energy. The secondary mechanisms for the photo-initiator modified coatings can be ambient moisture for the silicones (SR), and catalyzed, heat, aerobic, or ambient moisture for the organic AR, ER, UR, and ARUR materials. Aerobic UV chemistries are not totally effective depending on the fillet formation thickness and the ability for ambient air to diffuse through and penetrate the coating fillet The wavelength, intensity and duration of the UV source should be verified with the appropriate material supplier.

8.9.5 Moisture Cure Moisture cure materials react with ambient moisture. The available relative humidity at the time of exposure has a direct impact on the speed of cure initiation. Caution should be exercised to prevent premature cure initiation due to storage or application conditions.

Because moisture in the atmosphere will penetrate the coating and initiate cure these materials cure from the outside in, and typically cure only to a depth of 6.35 mm [250 mil]. For coating applications that require a thickness greater than a few mils, anticipate a longer cure time. As with room temperature cure coatings, moisture cure coatings can also be accelerated by mild elevation of temperature and humidity. The temperature used is typically no more than 65°C [149°F]

8.9.6 Catalytic Cure Catalytic coating materials cure by a reaction between two parts. Catalytic materials start to cure once the two components are in contact with each other. Usually, a primary cure mechanism, such as UV or heat, is generally incorporated into these materials to speed up the cure Catalytic reaction allows UV curable materials that are not irradiated by UV, such as coating 'shadowed' under components, to cure with no added process steps or induced stress on the components, solder joints, or coating fillets Catalytic cure is popular with solvent-free organic materials

8.10 Cure Process Considerations Characteristics of "cured" conformal coatings are provided in the material supplier's technical data sheet. If the recommended curing conditions of the supplier are not strictly followed, end results vary

Cure is defined as completion of chemical reaction and full development of properties. Adhesion is typically the last property to develop. This may be several hours to several

days depending on the conformal coating chemistry. Consult the material suppliers for cure schedules. If final testing and or "burn in" are anticipated after the coating operation, the time taken for the chosen material to reach optimum properties needs to be considered.

8.10.1 Cure By-Products Some coating materials can produce by-products as a result of the curing chemistry employed. Some silicones may produce methanol in small amounts and others evolve cyclics, which can produce a micro-layer of silica on or near mechanical relays and read/write heads. Because so many chemistries are available, the user should contact the conformal coating supplier to understand what by-products and volatiles may be produced as a result of a particular product chemistry.

For products that do form a by-product it is necessary to verify what the by-product is and utilize only materials with a noncorrosive by-product. Many silicones used as conformal coatings may liberate methanol as a by-product and this is considered a neutral-cure or noncorrosive product. Products to avoid in conformal coatings applications are acetoxy-cure silicones since they liberate acetic acid

8.10.2 Exotherm Catalyzed materials or materials that contain two parts can usually generate exothermic heat as part of the curing reaction This is not a problem in the conformal coating application or curing process because thin films are applied. The exothermic temperatures of the thin films are so insignificant that they cannot be plotted <0.254 mm [<10 mil].

Material mixed in large bulk (>1 liter) [>0.26 gallon], can reach very high exothermic temperatures if not used within the pot life and left to cure in large quantities It should never be left in fluid delivery systems or reservoirs past the recommended pot life. This should also be verified with the material supplier.

8.10.3 Shrinkage Some coatings use solvents/thinners to adjust the viscosity for the various types of application processes. These additives increase the volume of the material from 10% to over 80%. As these solvents evaporate after application, there will be a certain amount of "shrinkage." In addition to shrinkage due to solvent evaporation, there is shrinkage due to the generation of by-products Shrinkage can cause exposure/voids on sharp angles, edges, points, or other irregular shapes.

Shrinkage can also lead to residual stresses particularly around the component substrate interfaces. Wide variations in thickness can produce additional strains on the coating, solder joints and components. The thicker areas around the fillets become residual stress concentration points. CTE mismatches between the metals and plastic can lead to cracked solder joints and/or components. The greater the mismatch the quicker this occurs. The stresses can also be amplified by rapid temperature changes because polymers have a very slow rate of thermal transfer

Reducing the thickness variations is the best method of reducing residual stress

8.10.4 Premature Surface Cure/Solvent Entrapment Due to the highly competitive nature of electronics manufacturing, processes are always monitored for methods to save costs. Reducing the cure/dry cycle is one of the simplest ways to speed production. Unfortunately, this effort to save money, no matter what it costs, can create serious reliability problems.

Rapid curing can cause a "skin" to form on the surface of coatings that will prevent the thinners/solvents from evaporating. This can result in bubbles/voids in the coating as well as preventing the cross linking of polymeric chains for certain types of materials. Some solvents can attack the substrate or solder masks when left exposed over extended times. Other thinners, such as water, can attract and dissolve ionic contaminates.

Uneven thickness of coatings due to surface tension wicking around the components, can also create the same problem. This "localized" entrapment is the worst possible location because solder joints and component casings are placed in jeopardy

Solvent/thinner entrapment can also occur if the coating completely underfills the space between the component and substrate preventing evaporation This can lead to problems that are not visible unless the component is removed.

Any proposed changes to a successful coating and curing operation should be thoroughly tested before being implemented into production.

8.10.5 Exceeding Cure Recommendations While under-curing a coating may lead to an incomplete development of film properties, over-curing may lead to some adverse effects on the performance of coating. Depending on the chemistry and cure mechanism, exceeding the cure schedule and conditions recommended by the material supplier may lead to embrittlement, discoloration, formation of ripple, etc.

8.10.6 Layering Some chemistries need to be cured completely before the next layer is applied to achieve desired thickness. Some chemistries cannot adhere to themselves if not fully cured.

8.11 Application Process Monitoring The monitoring of the conformal coating process should be sufficient to guarantee consistent and reliable application and cure of these materials. The coating process is usually the last assembly step in the electronic assembly process and a mistake here

could be significant. Some equipment is available that automates the monitoring process and may self-correct the application. Many process monitors can be employed. A simple witness coupon can be run along with the parts to measure wet coating thickness, dry coating thickness, general appearance of the coating and degree of cure Many statistical process contro. (SPC) monitors can be incorporated into selective coating lines such as coating confirmation via the fluorescent tracer dye added to most coating chemistries The coating and cure process should be monitored and documented to insure and demonstrate reliable yields

8.12 Inspection Guidelines See IPC/EIA J-STD-001, IPC-HDBK-001, and IPC-A-610 for further discussion.

Once a PCA has been coated, it is important to inspect, or evaluate the success of the process. Most often, a visual inspection is employed. During inspection, an operator may be evaluating a variety of criteria, including:

- Coating coverage (8.4) and integrity of masked areas.
- Coating thickness and uniformity.
- Voids in coating/air entrapment.
- Bridging.
- Workmanship.

Inspection can be done before and/or after curing has taken place. This depends on your specific process and the ease of rework and repair of your coating.

Many types of coatings have fluorescent tracers. This is to make inspection much easier. Placing a PCA under a black or UV light causes the tracer to fluoresce so an operator can easily detect coated and noncoated areas.

Visual inspection is not as common in selective or robotic applications due to the large number of assemblies coated in the production. In these applications, automatic quality control options are available. Presence sensors can verify that coating has been placed on a particular spot on the PCA. This cannot, however, confirm coating thickness, uniformity, or placement aside from a particular spot. Flow meters can verify the volume of coating that has been applied to each PCA, while preventing out of tolerance parts from continuing in the process.

8.12.1 Magnification When using magnification in the inspection process, 2x to 10x enlargement is sufficient Greater magnification may be necessary in suspected defect areas Magnification instruments should be at an acceptable resolution to assess the coating process Aids that permit simultaneous viewing with both eyes are always preferred, but not necessary.

8.12.2 UV/Light Source A low intensity UV light, or a fluorescent, shadow-less illumination light source may be used in an inspection process. Coatings that possess a UV tracer fluoresce under a black light, thus making the inspection process a much easier task. The PCA should be placed anywhere from 50 mm - 152 mm [2 in - 6 in] from the light source for optimal evaluation

8.12.3 Workmanship Workmanship of the conformal coating application process needs to be evaluated to ensure that the applied coating fulfills the specified requirements Regardless of the application method, the applied film should not exhibit de-wetting behavior. The cured coating should be free of blisters or breaks that will cause poor sealing and eventually cause corrosion. It should be free of voids, bubbles, or foreign material and contain no mealing, peeling, wrinkles or nonadherent areas (Figures 8-17 and 8-18).

Assemblies coated by dipping may have a drip line or localized build-up on draining off the edge of the board. This build-up may contain a small amount of bubbles, which will not affect the functionality or reliability of the coating.

If de-masking is included in the process, workmanship of the de-masking step needs to be examined to ensure that masking residue and degradation of the coating or the board or the assembly is minimized. Forms of degradation include lifting of materials from substrate, peeling, cracking, lifting of edges, physical damage to the substrate and/or components.

For examples of applicable accept and reject criteria, see J-STD-001 and IPC-A-610

Figure 8-17 Loss of Conformal Coating Adhesion

8.13 Environmental, Health and Safety Processing Considerations There are several safety guidelines that should be followed during all parts of the conformal coating process. First and foremost is basic cleanliness and

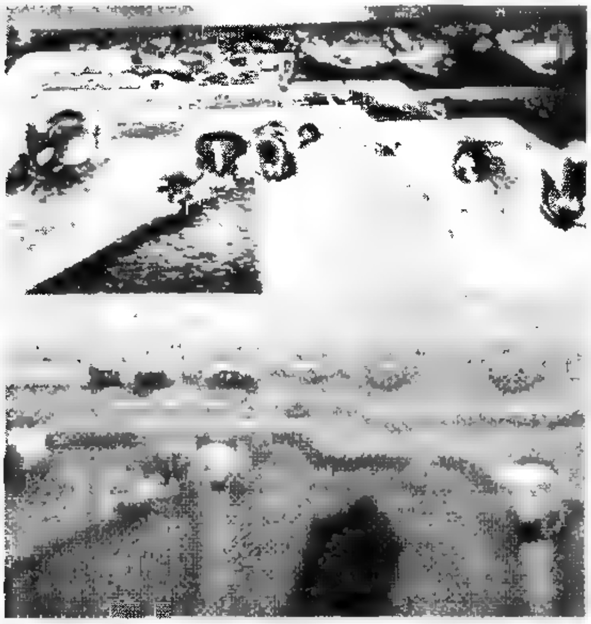

Figure 8-18 Voids in Conformal Coating

caution. All work areas should be kept reasonably neat, spills should be cleaned up immediately, food or drink should never be in work areas, and eye protection should be worn at all times in the manufacturing environment. Also, material safety data sheets (MSDS) should be available for all coatings, solvents, strippers, etc. used in the conformal coating process. These MSDSs should be located in an area which is accessible to individuals working with the chemicals and materials contained therein. Anyone working with a particular coating, solvent, etc. should review the MSDS on site and be sure to follow the safety protocols listed for that particular material.

Any application method brings health and safety concerns to the user. Manual operations should address operator issues even more seriously, as the employee may have direct contact with the spray process. Common hazards associated with conformal coating applications are inhalation/ventilation and skin irritation. Proper ventilation in the area where conformal coatings are applied, cured, and reworked is very important. Also, most conformal coatings are irritants and contact with skin should be avoided. It is suggested that gloves and other appropriate protective gear should be used when handling conformal coatings. Consult with in-house health and safety professionals, if available

8.13.1 Viscosity Adjustment Coating manufactures are familiar with the environmental impact that using solvents have. This has lead to the reformulation of several popular solvent-based coatings. These new solvents are not as regulated as the older traditional solvents (xylene, toluene, methyl ethyl ketone). The reformulation allows companies to continue using older coatings without being faced with fines for VOC emission. They can continue to rely on the same coating performance without having to evaluate new coatings. Refer to your local authorities for regulatory requirements on solvent used in viscosity adjustment.

8.13.2 Spraying Ventilation is of primary importance when performing spray applications of conformal coatings. When manual spraying, the process should be performed in a ventilation hood, with the user employing a dust mask or a better form of inhalation protection. An automated spray process should have its own ventilation as part of the equipment. In addition, all the standard safety guidelines should be employed: eye protection, skin protection (gloves, lab coat), no food or drink, and a neat work area.

The MSDS for any solvents used for thinning should be reviewed and the appropriate safety protocols employed. For instance, if the solvent used is flammable, storage should be in approved flammable safety cabinets.

8.13.3 Dipping and Brushing When applying conformal coatings using either the dipping or brushing method of application the standard safety guidelines should be employed: eye protection, skin protection (gloves, lab coat), no food or drink, and a clean work area. In addition good ventilation in the work areas are also important. This is especially true with the brush application. People applying the conformal coating via brush, should avoid working for long periods of time with their faces close-to and directly above the work area, inhaling high concentration of fumes.

The MSDS for any solvents used for thinning should be reviewed and the appropriate safety protocols employed. For instance, if the solvent used is flammable, storage should be in approved flammable safety cabinets.

8.13.4 Vacuum Deposition The use and operation of the vacuum deposition equipment should be well understood and any safety issues regarding the equipment should also be reviewed periodically. In addition, all the standard safety guidelines should be employed: eye protection, skin protection (gloves, lab coat), no food or drink, and a neat work area.

8.13.5 Curing During the curing process of conformal coatings solvents are often given off. Therefore adequate ventilation should be used during this process. When employing ultra-violet curing methods, care should be taken to avoid eye and skin exposure to the UV energy.

9 FILM PROPERTIES

All polymeric conformal coatings have varying physical properties, depending on the polymeric backbones and other modifying chemical elements or additives. When selecting a coating for an application, the designer should be aware of:

- The physical properties of cured coatings. Example: a coating with no resistance to salt air would not be a good choice for Navy hardware.
- How these properties may change from published values as a result of variables in the coating operation. Example: rise times and propagation delays may be affected dramatically if a coating is used that is drastically beyond its shelf life.
- How these properties may change with time as a result of the end-use environment. Example: coatings may be embrittled or darkened with exposure to high heat.
- 'Qualified' or 'Approved' coatings to the various standards and specifications given in Section 2 of this handbook will have been tested to verify that the following issues have been addressed. It is recommended that the relevant coating manufacturer be asked for a copy of the test reports.

9.1 Appearance/Color The transparency of the coating is often an issue for hardware. A customer may need to read the identifying marks on the PCA surface, or a field service technician may need to see the component leads before attempting repairs. Most specifications require that the coatings maintain their transparent properties. Desired appearance and transparency should be maintained through various environmental stress screenings.

9.2 Dielectric Properties Conformal coatings, when applied to the PCA, become a part of the dielectric system, affecting electrical parameters. If this is not taken into account during the design, then the circuit may not function as desired.

9.2.1 Dielectric Withstanding Voltage (DWV) Dielectric Withstanding Voltage is a measure of how well a coating resists conducting electricity, usually at a high test voltage, for a set period of time. Most modern coatings may withstand 5000 volts for 60 seconds. DWV should be a consideration when designing high voltage equipment or equipment exposed to high amounts of corona.

9.2.2 Insulation Resistance Insulation resistance is a measure of the resistance to the flow of electricity. The higher the insulation resistance, the better the material is as an insulator.

Moisture resistance, sometimes also called moisture and insulation resistance (M&IR) is a measure of how well the insulation characteristics are maintained when exposed to elevated conditions of temperature and humidity. A material with a low M&IR value would be a poor choice to protect a circuit in a high humidity end-use environment.

9.2.3 Q-Resonance As stated before, conformal coating polymers become part of the dielectric equation when they are applied to a PCA surface. Some of the dielectric properties of a coating are dependent upon the electromagnetic frequencies experienced. When hardware operates at high RF frequencies, the coating may alter the response of the circuit as its dielectric properties change with frequency.

9.2.4 Dielectric Constant and Dissipation Factor Dielectric constant and dissipation factor are a measure of how much a material may slow down electromagnetic propagation or how much energy an electromagnetic signal may loose. Materials with very low dielectric constants, such as polytetrafluoroethylene (PTFE) or ceramic, have very low dielectric constant and dissipation factors. An RF signal does not lose much energy and rise/fall times are only minimally effected for these substrates, which is why they are chosen for high-speed/high-frequency hardware. In contrast, a material with a high dielectric constant may cause excessive energy loss in RF signals.

As with the Q-Resonance, dielectric constant and dissipation factor are frequency dependent. Standard test frequencies for materials are 1 KHz and 1 MHz. High dielectric constant materials are often used in DC power applications, since there is no frequency effect at DC. It is important to consider the changes in dielectric constant and dissipation factor brought about by the addition of conformal coating into the dielectric balance. Ideally, the coating should be the same dielectric constant and dissipation factor as the substrate material, but this is often not possible.

9.3 Thermal Properties Thermal properties of a conformal coating are an important characteristic because the coating should be able to withstand local hot spots generated by components or from environmental temperature exposure of the electronic device it has been applied to. Some end-use applications may involve extreme temperature, or widely ranging temperature. For example, automotive (11.2), space (11.4) and geothermal (11.6) applications. Thermal profiles, which include ambient and operational temperature extremes, should be considered when selecting coatings. When temperature changes, other conditions, e.g., humidity and pressure may vary too. It is advisable to evaluate all these potential changes and their affect on conformal coating.

Thermal analysis techniques can be used to determine coating properties with changes in temperature such as:

- The useful state of cure.
- Glass transition temperature.
- Degree of cure.
- The amounts of moisture and volatiles present.
- Mechanical properties such as expansion, contraction and modulus

Examples of thermal analysis techniques are differential scanning calorimetry (DSC), thermal mechanical analysis (TMA), dynamic mechanical analysis (DMA) and thermal

gravimetric analysis (TGA) More information on these techniques can be found in Appendix D

9.3.1 Thermal Stability High temperature can cause short-term changes in coating characteristic such as softening and potentially lower electrical resistance. Long-term effects of high temperature operation can cause coatings to discolor, embrittle, crack, and shrink, effecting dielectric strength and insulation resistance. Low temperatures can cause cracking and delamination due to differences in CTE, vibration, or flexing Thermal cycle testing, using dummy components, is recommended to determine suitability for each application

Silicones are generally used for extreme temperature cycling environments Typically, they can be useful from -55°C to +200°C [-67°F to +392°F]. Silicones are elastomeric, pliable and present a lower risk for solder joint or component damage at extreme temperatures. Poly-para-xylelenes (parylenes) are relatively stable up to 250°C [482°F] in the absence of oxygen, 120°C [248°F] in the presence of oxygen. Flourinated poly-para-xylelenes (parylenes) are relatively stable up to 450°C [842°F] in oxygen. Organic materials such as AR, UR, ER and ARUR offer useful operating temperature ranges from -40°C to +125°C [104°F to 257°F]. The latest water-based coatings can offer performances between -65°C and +200°C [-85°F and +392°F]

9.3.2 Thermal Shock Thermal shock, higher than 30°C [86°F] per minute, may also stress the coating due to a slow delta temperature rate. This can cause cracking and delamination of some brittle coatings from internal CTE mismatches. IPC-TM-650, Test Method 2 6.7.1, is an example of a thermal shock test, which verifies the compatibility of a coating with a specific temperature profile.

9.3.3 Glass Transition Temperature (T_g) The Glass Transition Temperature (T_g) is the temperature at which an amorphous polymer transitions between a super-cooled liquid and its glassy solid. As a result, amorphous polymers exhibit substantially different physical properties above and below this characteristic temperature. The T_g is strongly dependent on the rate at which the temperature changes through this phase change.

9.3.4 Coefficient of Thermal Expansion (CTE) The Coefficient of Thermal Expansion (CTE) is the linear dimensional change with respect to an original dimension due to a change in temperature. Two measures of CTE are usually provided: one in the X-Y plane (lateral) and one in the Z-direction (thickness). CTE is also generally reported above and below the Glass Transition Temperature. Ideally the CTE should be as close as possible to the same between the substrate, component, solder alloy and coating. Some users express this as Thermal Coefficient of Expansion (TCE).

CTE is an important design consideration because if the thermal expansion characteristics of the coating are radically different than for the substrate, cracking of the coating may occur, compromising coating integrity. and the coating may unduly stress component lead-to-body seals, compromising reliability This is particularly true for the more rigid coatings, such as epoxy If the end-use environment has large or rapid swings in thermal conditions, a CTE mismatch can prematurely fatigue a coating or cause fatigue failures in components.

9.3.5 Temperature Gradient Temperature gradient across a conformal coating layer may induce undesirable stress to the coating even when its CTE matches with that of the PCA This may lead to cracking of the coating.

The rate at which a coating layer stabilizes to a minimum temperature gradient is a function of the specific heat capacity and the heat transfer coefficient of the coating. Coating with a high specific heat capacity or a low heat transfer coefficient may have a localized hot spot for a longer period. These properties need to be considered if the end use environment has large or rapid swings in thermal conditions.

9.4 Flammability Conformal coating is a permanent feature on a PCA; it covers most of the components and printed circuit board surfaces. Therefore, it has the potential to either isolate or propagate the effect of any electrical short that might occur. Flammability of the coating material is an important property to consider when selecting a conformal coating, especially if it is for an end use environment susceptible to combustion

Some coatings contain flame-retardants. Flammability of conformal coatings can be tested per ASTM D 635 or FAR §25 853 and/or certified to UL746C or UL94 (vertical and horizontal burn tests) when required Users should familiarize themselves with appropriate specifications for their applications

9.5 Flexibility Flexibility is needed for temperature variation and physical flexing of the PCA. The lower the temperature the more brittle coatings become. Young's Modulus, or modulus of elasticity, is temperature dependant A material with a low modulus, such as a silicone, is flexible yet virtually incompressible at high rates of stress. A material with a high modulus, such as an epoxy, is rigid.

Vibration and PCB flexing are the main components of expected physical motion. Vibrations and PCB flexing at lower temperatures pose the most threat to coating integrity All PCBs, including rigid PCBs, flex with temperature changes. Therefore, the flexibility of a material should be

taken into consideration when there are large thermal variations/cycles in the end-use environment

Flexibility testing is recommended primarily at the lower extremes of the expected temperature range for the product. Flexibility could be tested per IPC-TM-650, Test Method 2.6.11.1. These tests should include vibration and flexing of circuitry with components on them. In addition to inspecting for cracking and delamination, solder joints and components should also be observed for signs of damage.

Effect of high modulus coating on glass body components should be evaluated using thermal cycling test when wide temperature ranges are expected. For high reliability applications, the flexibility test should include resonance vibration frequencies to replicate the end use environment.

One should consider modulus and CTE together when designing electronic controllers (especially with fine-pitch components). Silicones are generally good encapsulants due to their low modulus, even though they have a high CTE (~300 ppm/°C).

9.6 Abrasion Resistance Potential for mechanical abrasion should be considered when selecting a conformal coating. This may occur due to improper handling, storage or shipping and may result in scratches, scrapes, dents, creases, and marred surfaces which can become areas of concentrated stress or contamination ingress. Coated assemblies in direct contact with other subassemblies, such as wire harnesses, may abrade the coating. Excessive handling, insertion and removal of PCAs may also cause abrasion. High velocity air flow caused by venturi situations may erode coatings due to dust particles in the air stream.

9.7 Coating Creep Over time, coatings may move slightly under the influence of gravity or some other forcing function (e.g., air flow). Coating creep is usually more pronounced in the flexible coatings as they are less rigid. Conversely, rigid coatings tend to be less susceptible to this phenomenon. Also, particles, fibers, and other foreign material deposited on the coated surface may become encapsulated in the coating material as if the coating has melted and then solidified again. This may cause degradation of the protection afforded by time. These conditions can be amplified if the coating exceeds T_g (Glass transition Temperature).

9.8 Hydrolytic Stability Some end use applications may require the coating to be in contact with moisture consistently. Others may have moisture condensing on the surface of the coating occasionally. For both scenarios, the coating may be required to maintain its properties for a specific length of time. Coatings that are not hydrolytically stable would experience degradation of properties after exposure to a humid environment.

At the molecular level, aqueous layers of water begin to form when the RH reaches 40%. At 60% RH a layer of water 2 to 4 molecules thick can be present. A layer 3 to 4 molecules thick is enough to cause chemical reactions to begin with any hygroscopic particulates on the surface. At 80% humidity the aqueous layer is up to 10 molecules thick and deposited materials begin to dissolve. This creates free flowing ions which are capable of penetrating coatings. The presence of hydrocarbon compounds can aid the formation of aqueous surfaces layers on materials.

The general rule is when RH is ≥60% problems may occur. Experimentation has shown that submicron dust particles in the atmosphere can be acidic or basic when exposed to humidity ≥60%. At humidity ≥ 80% ion flow begins which can lead to leakage currents, dendritic growth, and corrosion. Any of these conditions: gas, acids, and submicron dust, can degrade circuitry with or without power applied to the circuit. Refer to 8.1.3. See also Appendices E through I for more information.

IPC-TM-650, Test Method 2.6.11.1, verifies the hydrolytic stability of a coating by examining the potential of the coating to turn into liquid or powder forms when exposed to high humidity at a specific temperature.

9.9 Permeability Permeability refers to the ability of one material, such as water vapor, fumes, particles, etc., to flow through another, such as a coating. All organic materials are permeable to some degree, depending on the chemical composition involved. Coatings such as epoxies may be more resistant to pollutant gasses, such as H_2S, than silicones.

Permeability is an important factor to be considered for the selection of conformal coating, especially if it is for applications in humid or corrosive environments. Permeability of a coating may increase when the coating is degraded by chemicals in the end-use environment. Moisture and gasses that permeate the coating may accumulate on the conductive surface of PCAs, leading to leakage currents, dendritic growth, corrosion and delamination of coatings over the surface.

The polymer matrix for all coating types is larger than the size of water molecule. Therefore, all coatings are water permeable. As a result, it is only a matter of when the water vapors get through, not if the vapors get through. However, with good adhesion and no voids, moisture protection can be achieved. In fact, low permeability of water may be disadvantageous since it will take a longer time for a PCA to dry up. When the polymer absorbs moisture, the dielectric properties can be affected. Thus, it is not recommended to submerge a coated PCA in any liquid material for an extended period of time. If submersion is a requirement of the end use environment, a sealed enclosure should be considered and long term compatibility of the coating with the liquid should be evaluated.

Variations in permeability may also occur with temperature changes. If the Glass Transition Temperature (T_g) of the coating material is exceeded these variations are quite large.

The permeability of conformal coatings can be tested using the following test methods.

- **ASTM E96** (Current Revision) Standard Test Methods for Water Vapor Transmission of Materials
- **ASTM D570** (Current Revision) Standard Test Method for Water Absorption of Plastics
- ASTM F1249 (Current Revision) Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using Modulated Infrared Sensor
- **ASTM D3833** (Current Revision) Standard Test Method for Water Vapor Transmission of Pressure Sensitive Tapes

9.10 Chemical Compatibility and Chemical Resistance Conformal coatings may be exposed to various chemicals in their end use environment. Examples of chemical exposure includes the common ones such as pollutant gases, fuel and cleaning media, to application specific chemicals such as body fluid and nuclear biological chemical warfare agents. This often includes formic acid deposited onto the PCA by insects that may ingress the PCA enclosure. When coatings are selected, the chemical compatibility of the coatings should be considered if contact with these agents is possible. Coatings are required to be resistant to these chemicals, i.e., not degraded by them, and to be able to protect the PCAs from any undesired effects of these chemicals.

Bilateral chemical compatibility may be important in some applications. In these cases, it is important to ensure that the coating materials would not pollute or degrade the end use environments or other products that they are in contact with.

9.10.1 Fuel Resistance In the end use applications where the coated PCAs have the possibility of coming into contact with fuel and/or machinery fluid, the compatibility of coating materials with these substances should be verified by the end users. Petroleum based products, e.g., petrol, jet fuel, diesel fuel, etc, may act as organic solvents that may attack some coating types. Hydraulic fluids and coolants may also contain chemicals that may degrade the quality of the conformal coating and thus, long-term reliability of the product.

9.10.2 Biological Compatibility For medical applications, there should be a bilateral long-term compatibility and nonreactive relationship between the coating and body fluids (e.g., blood, urine) and tissues. It should not contaminate the substrate with outgassing or byproducts from its catalysts, solvents, or plasticizers that could be harmful to the patient. See 12.5 for more information on applications in medical environments.

9.11 Gas Resistance For applications whereby the PCAs are exposed to gaseous environments, users need to consider gas resistance from two aspects. First is the permeability of conformal coating to these gases. The gases may not be harmful to the coating, but may have negative effect on the conductive surface, e.g., gases which dissolve in moisture and react with surfaces, leading to electrical failure. Second is the chemical compatibility of the conformal coating to these gases. See 9.9 for permeability consideration and 9.10 for chemical resistance.

9.12 Corrosion Resistance Moisture and ionic species may result in corrosion. Conformal coatings may inhibit or delay penetration of moisture to the PCA surfaces, thereby increasing corrosion resistance. Corrosion resistance is thus heavily dependent on permeability of the coating. Good adhesion, elimination of pin holes/voids, and appropriate thickness would minimize the potential of corrosion.

The ionic species needed in mechanisms of corrosion may permeate onto conductive surfaces from environments outside the coated PCAs. However, there may also be corrosive species on the PCAs (process residues including flux, uncured solder mask and handling contamination). Coatings can inhibit mobility of ions on the surface and hence enhance corrosion resistance. Proper cleaning and baking of the PCA prior to coating is highly recommended to prevent this type of corrosion. See 8.1 for cleanliness requirements.

9.13 Fungus Resistance Most specifications require that a conformal coating not support fungus growth. Some coating materials may contain fungus resistance chemicals. Also, fungus resistance of a coating should be considered for biomedical applications and hardware that is exposed to environments that are conducive to fungus growth. Even though some coating materials may be fungus static in nature, cleanliness of the coated assemblies should be maintained to avoid fungus growth on residues; for example, finger prints might encourage fungus growth. Fungus resistance may be tested using IPC-TM-650, Test Method 2.6.1.1.

9.14 UV Stability If the hardware will be exposed to ultraviolet radiation, such as outdoor use or space applications, the coating should not be degraded or measurably altered by exposure to UV light. Some coatings have additives that absorb UV light before it can degrade the polymer structure. These additives are most often called UV inhibitors. Darkening or yellowing of the coating after exposure to extended UV light is normal. The detrimental

affect of UV exposure on the coating would be demonstrated by embrittlement, cracking, crazing, etc

Some coatings may be stable in outdoor use applications, but not vacuum stable, and thus not suitable for space applications. Other coatings may be unstable in outdoor use applications, but stable in the absence of oxygen and thus suitable for space applications. This signifies the importance of considering the entire environment in which the device will reside

9.15 Radiation Resistance Material properties affected by radiation in space (nuclear particles and electromagnetic radiation) are mechanical (tensile strength, elasticity, elongation, hardness, etc.), thermal and optical properties.

Polymeric substances exhibit a wide variety of radiation effects that are irreversible. The radiation stability of a polymer is dependant upon the chemical structure of the material because radiation induced excitation is localized to specific chemical bond. Addition of energy absorbing aromatic rings to the chemical structure of the polymer greatly increases radiation stability of the polymer. In general, polymers containing aromatic rings (benzene) are more resistant than those not containing it.

Depending on the chemical type of coating used, radiation can lead to chain scission or increased cross-linking, with chain scission being typified by a softening or tackiness to the coating and cross-linking leading to a more rigid and brittle coating. When the polymer backbone of a coating is altered by these mechanisms, the physical and electrical properties can change, affecting hardware reliability. Radiation resistance needs to be considered for hardware that will encounter high-energy radiation, such as from nuclear reactors, x-ray equipment, all space-related hardware, medical sterilization etc.

9.16 Outgassing Some conformal coating materials contain plasticizer agents, especially elastomers, thermoplastics, and other flexible materials. Over the course of time, under certain conditions, the coatings may emit these agents, becoming more brittle in the process, as well as possibly contaminating nearby surfaces with the outgassing products. In addition to these agents, some coatings contain unreacted low molecular weight species that may also outgas under certain conditions.

Some conformal coatings outgas significantly, making them unsuitable for space applications. The vacuum of space tends to pull the agents out faster and causes outgassing. Outgassing species may cause problems where optical clarity is paramount in systems with lenses, mirrors and viewing ports. Outgassing resistance is also important where unsealed relays, switches or separable connectors are used. Outgassing products such as cyclics, low molecular weight species, dyes and some fluorescent chemicals added to the coating materials may form insulating deposit on electrical contacts, possibly causing electrical failure. ASTM E-595 or NASA equivalent specifications may be used to screen materials for outgassing. To avoid outgassing, care should be taken to ensure complete cure has occurred.

10 REWORK AND REPAIR

For minor or localized board and component reworks/repairs, all conformal coatings classes can be reworked/repaired. If rework/repair is determined as necessary then the AR conformal coatings are best suited for ease of rework and repair. More information about rework and repair procedures can be obtained from IPC-7711 and IPC-7721.

10.1 Removal Methods Complete and partial removal methods of the conformal coating from PCAs can be accomplished with techniques such as chemical solvent stripping, mechanical abrasion removal, micro-abrasive media removal, dry ice abrasion, thermal degradation, excimer laser and plasma stripping. In most cases only a selective localized site of conformal coating needs to be removed to replace a defective component

10.1.1 Chemical The chemical removal techniques involve swelling the coating with a solvent to chemically break down the coating and to reduce the adhesion between the coating and the board sufficiently to float the coating. This technique is applicable to large areas or the entire board. One problem with partial coating removal is the diffusion of liquid into areas other than the area to be removed The compatibility of solvent should be verified with the PCA prior to use.

Either dipping or spraying the solvent onto the coating can be used to remove it. A supersonic spray cleaner may be used to remove the coating in localized areas of the PCB. Use of chemical strippers should be limited because they can be corrosive and difficult to clean, especially if they get into nonhermetically sealed components.

AR conformal coatings are the simplest to remove via solvent submersion. The solvent softens the coating and allows removal by additional swabbing or light abrasion with a scraping tool being careful not to damage the substrate. Some conformal coatings may be dissolved fully into the solvent solution and swabbing may not be necessary. After removal the area is neutralized via ample rinsing with deionized or distilled water and then heated in an oven 82°C to 93°C [180°F to 200°F] dependent on the substrate's resistance to temperature) The heating is best performed in a vacuum oven 100 Torr [30 lbs gauge pressure or 1.934 PSI] for approximately one-hour to assist in pulling off any contaminants.

10.1.2 Mechanical Abrasion This involves rotating disks, grinders and cutting tools. Caution needs to be exercised to prevent removal of substrate material below the coating level and subsequent underlying structure damage. Mechanical methods also include surgical incisions, which are made directly on the solder joints. This method is usually used in conjunction with solder extraction of the solder fillet through the excised incision.

10.1.3 Media Blasting Media blasting utilizes high velocity abrasive media directed through a nozzle to locally abrade the coating. Media includes plastic pellets, glass beads and ground walnut shell particles Most systems are designed to control electrostatic discharge from the rapid movement of the high velocity abrasive media

Users are cautioned that significant ESD damage may occur to ESDS sensitive items in event the machine used does not have built-in ESD controls, or otherwise, in the event the controls fail or the humidity drops below 30%. It is recommended that the voltage generated at the nozzle dispensing the power be verified as within an acceptable range during each daily use of the machine.

10.1.4 Dry Ice Abrasion Micro-sized carbon dioxide pellets are blasted at localized areas of coating to be removed. With this technique the coating would be removed by impact coupled to low temperature coating embrittlement and fracture.

10.1.5 Thermal Degradation Thermal degradation involves the use of a soldering iron or thermal parting tool (hot knife or air jet) to locally melt the conformal coating. Care needs to be taken to prevent charring and resulting thermal damage to the pads and substrate Fumes should also be extracted.

All conformal coatings classes (AR, UR, ER, SR, and XY) can be reworked/repaired via thermal removal of the board/component. Thermal rework/repair of conformal coatings can be softened and charred to facilitate in the removal of the required areas using a localized hot air jet or hot-knife at 300°C to 400°C [572°F to 752°F]. The coating can be chipped or flaked easily off the substrates with minor surface abrasion. After removing the coating the substrate should be solvent cleaned with IPA and neutralized as with the chemical removal in 10.1.1 prior to recoating.

10.1.6 Laser This is an elaborate method of laser ablation removal. The systems are expensive and are generally used for small-localized areas of coating removal on microelectronic assemblies.

When electromagnetic radiation is absorbed by organic polymers, the polymer molecules become excited (heated). When the radiation beam has enough power to heat the polymer sufficiently to produce a vapor pressure then the polymer is volatilized. If the photon energy ($E=hc/\lambda$) is sufficient to break chemical bonds, volatile compounds are produced. Thus laser radiation can remove conformal coatings from PCAs by two mechanisms:

- Coating melting and vaporization.
- Chemical photo-degradation of the coating.

Adequate radiation exposure time is required to complete the coating removal from the desired area by either mechanism Less laser beam power is required for photo-degradation than for ablation. Ultraviolet lasers are required for photo-degradation whereas other lasers are used for melting and vaporization By focusing the laser radiation beam, small coating areas can be removed. Further upon sweeping the beam the entire coating can be removed by either process. With either technique, care should be taken to ensure no damage to the PCB and its electronic components.

10.1.7 Plasma The plasma removal method is commonly used for removal of the poly-para-xylelenes (parylenes). It requires a vacuum system, an electromagnetic radiation source, and a gas supply. Either radio-frequency (103-109 Hz) or microwave frequency (109-1012 Hz) sources can be used. Plasma etching mechanisms are divided into four categories:

- Sputtering mechanism.
- Chemical mechanism.
- Ion enhanced energetic mechanism.
- Ion enhanced inhibitor mechanism

In the sputtering mechanism ions mechanically eject coating material at low pressure whereas thermalized neutral gaseous radicals react with coating material to form volatile products in the chemical mechanism. The ion enhanced energetic mechanism is characterized by little or no intrinsic surface reaction with neutral radicals until energetic ions increase the reactivity of the coating producing chemical reactions which form volatile molecules from the coating. By depositing an inhibitor to exclude etchant in working areas, small localized areas can be etched by the ion energetic mechanism. The plasma etching processes are characterized by rate, selectivity, uniformity and surface quality The electromagnetic source variables are:

- Electric field to number density.
- Product of number density and characteristic reactor length.
- Generator frequency, number density product.
- Reactor shape and aspect ratios Gas pressure directly influences the etching mechanisms.

If this method is used, caution should be taken to avoid damage to the PCA

10.1.8 Combination Rework Methods In many cases, combinations of the above methods of removal will provide the most efficient and effective method of conformal coating removal. Each rework situation is different and consultation with the material supplier will determine the most suitable method(s) of conformal coating removal for a particular coating type or chemistry.

10.2 Cleaning After Stripping A conformal coating stripping operation most often involves exposure to solvents, which soften or dissolve organic polymers If these materials are left on the substrate, which is also an organic polymer system, the stripping agent does not know where to stop. Often, these materials contain halides or other materials which can also attack metals, resulting in corrosion or metal migration on the PCA. Therefore, it is critical to completely remove these materials from the item being stripped.

The cleaning method used will depend greatly on the PCA involved and its susceptibility to the cleaning agents or solvents, and on whether the stripping operation was global or removal from only a limited area.

The manufacturer of the stripping agents should provide information on the best way to neutralize or remove their chemical materials. In most cases, deionized water can be used as a primary rinsing agent to reduce the amount of the stripping agent, and most coatings are not affected by deionized water. It is recommended that swabbing the stripped area with isopropyl alcohol NOT be used. This only tends to redistribute the detrimental materials, rather than remove them The critical endpoint of the cleaning is to get a substrate that is clean, dry, and ready for recoating.

Removal of Type UR conformal coating using certain chemical stripper gel or stripper solvents may leave conductive residues It is recommended that the assembly be cleaned with a combination of polar and nonpolar solvents under a pressure wash/rinse/dry cycle to ensure complete removal of any potentially harmful residues from the conformal coating stripping process.

If the board has been globally stripped, then rinsing and cleaning becomes easier Rinsing with deionized water is recommended to knock most of the stripping agent from the board If you have access to an ionic cleanliness tester, you can measure the amount of residual ionic contamination, as well as providing a mild cleaning action. If this option is used, check the PCA to make sure that it is not water or isopropanol intolerant.

10.3 Recoating It is often necessary to remove a defective component(s), from a previously coated and cured PCA to facilitate repair. Once the previous coating has been removed and the defective device has been successfully removed and replaced, the site should be cleaned of residual solder fluxes and be allowed to dry. See 7.3 for adhesion and cleanliness.

The degree of wetting and adhesion characteristics over the old coating may vary with chemistry Some coatings may not level out over the old coating at the same original thickness when applied, and may require 0.05 mm - 0.08 mm [2 mil - 3 mil] of material to be applied before the surface tension "relaxes" on the original coating. This should be considered if the PCA has strict coating thickness tolerances. In some cases an adhesion promoter or mechanical abrasion may be required to treat the new surfaces and the demarcation sites of the intact coating. Once any adhesion promoter is applied and cured, or abrasion technique is completed, the rework site is ready for recoating. It is important that the same or a compatible coating chemistry be used for recoat. The coating material can be applied by a brush or syringe to the rework area and be allowed to slightly overlap the original coating edges. For large recoat sites, the remainder of the board can be masked and the rework site re-sprayed. The coating material is then cured, inspected and is ready for service Users are urged to check with the material suppliers to confirm the recommended removal and rework techniques and any recommended adhesion promoters.

Caution Normally, different types of conformal coating should not be intermixed on the same assembly unless the user has determined that they are compatible with each other. For example, repairing an assembly (e g., replacement of a part that is conformal coated), that originally had Type AR coating applied. using Type UR coating, may cause inadequate adhesion between the two different coating types since the solvents in the Type UR coating can react (i.e., dissolve) with the Type AR coating and result in delamination between the coated areas

10.4 Environmental, Health and Safety Rework and Repair Considerations Any rework and repair method brings health and safety concerns to the user. Common hazards associated with conformal coating rework and repair operations are inhalation of stripping and/or coating chemicals and skin irritation caused by them, cut or score caused by the abrasion tools and media, and burns caused by the thermal parting tool. It is suggested that gloves and other appropriate protective gear should be used when reworking or repairing conformal coatings on PCAs Consult with in-house health and safety professionals, if available.

11 END USE ENVIRONMENT

End use environment is a vital consideration while selecting a conformal coating. How and where a product is going to be used determines what properties the coating materials are required to possess. Any coating should be thoroughly evaluated for end use environment compatibility. Coating

manufacturers may be contacted for specific data on considerations that are not listed in the material data sheet.

A few examples of end use environments for conformal coating are discussed below:

11.1 Outdoor Environment If a product is built for outdoor use and the PCAs are not hermetically sealed, conformal coatings may be exposed to the following conditions:

11.1.1 Ultraviolet (UV) Radiation Ultraviolet is an electromagnetic ray with a frequency just outside the visible light spectrum. Ultraviolet radiation is found in sunlight. It is scattered by the atmosphere to a greater degree than is visible light. Hence, even if the coating is not directly exposed under sunlight, it will still be susceptible to UV radiation. UV stability will likely be a requirement for the selection of conformal coating to ensure it performs in an outdoor environment

11.1.2 Humidity Products for outdoor application are subjected to various degrees of humidity. In temperate and warm climate zones, 30 to 60% of the time the relative humidity of the outdoor environment is higher than 80% when the atmospheric temperature is above 0°C [32°F]. In tropical climates, the humidity is generally higher.

Depending on the degree of humidity exposure, hydrolytic stability and adequate level of permeability will likely be the requirements for the selection of conformal coating. Corrosion resistance, which is a function of permeability, may also be required

More information about the concept of critical relative humidity and time of wetness can be found in Appendix E

11.1.3 Pollutant Gases Atmospheric pollutant gases typically consist of oxides of nitrogen and sulfur (NO_x and SO_x) which are byproducts of the burning of fossil fuel. These pollutants generate numerous ionic and hygroscopic microscopic compounds that absorb moisture and react among each other and transform into corrosive vapor on the surface of the coating. Resistance to pollutant gases and nitrogen and sulfur derivative acids will likely be a requirement for the selection of conformal coating if air pollution is a concern in the end use environment.

See Appendix H for more information on pollutant gases.

11.1.4 Ozone Ozone (O_3) is a very reactive gas. It has a short life expectancy when it comes into contact with other materials. It is capable of reacting with many forms of organics, including polymers and elastomers. Most polymers (e.g., conformal coatings) have additives to prevent direct attacks from ozone. Check with the coating manufacturer for ozone resistance if high reliability is expected from a coated PCA operating in an outdoor environment.

When moisture, organic compounds and other reactive gases are combined with ozone a wide variety of chemical reactions can occur. Some of them are capable of causing a break down in polymeric chains and or cross linkage.

11.1.5 Acid Rain Acid rain is a byproduct of combustion effluent and other VOCs (Volatile Organic Compounds) released into the air. A complex series of chemical reactions begin when these gases are combined with moisture and ultra-violet light. Ozone (O_3), sulfates (SO_x) and nitrates (NO_x) are the primary acidic constituents of "acid rain" (pH <5.0).

Because the amount of acid depends on exposure to sunlight (UV), moisture, and warm temperatures there is more acid generated in the summer then in the winter. The harder and longer the rainfall the less the amount of acid it contains as it is "washed" or "scavenged" from the air. Fog, drizzle, and mist may also be extremely acidic

Resistance to corrosion, specifically resistance to nitrogen and sulfur derivative acids will likely be a requirement for the selection of conformal coating if air pollution and acid rain is a concern in the end use environment.

11.1.6 Marine and Coastal Environment Populated coastal environments are capable of causing damage to electronic circuitry. Man-made pollutants combined with suspended sea salt and high humidity can create very conductive and acidic atmospheres. pH factors as low as 1.7 have been measured in fogs in southern California.

Suspended aerosols/particulates can be generally grouped into four categories; organic acids, marine substances, soot carbon, and inorganic salt. All these particles could become nuclei to absorb moisture and to further combine and react with other particles.

Hydrolytic stability, low permeability, acid resistance and moderate level of abrasion resistance are requirements for the selection of conformal coating for applications in marine and coastal environments.

For more information, see 11.1.2 on humidity, and Appendix G on atmospheric particulates.

11.1.6.1 Salt water Salt spray, mist, and suspended crystals may disrupt unprotected circuitry and may corrode the metals in circuitry. The corrosive effects may be greatly reduced at a distance of 3.2 km - 8.1 km [2 mi - mi] inland from the shore. The presence of microscopic amounts of salt may create intermittent operation depending on temperature and humidity Humid environments provide the aqueous layers necessary for chemical attacks to the coatings and circuits.

11.1.6.2 Fresh water Fresh water has fewer suspended materials (including salt) than salt water (11.1.6.1). Again, because of the higher levels of humidity an aqueous layer may be present.

11.2 Automotive Electronic devices intended for automotive applications are exposed to severe service environments. They are exposed to wide temperature extremes, many types of fluids, and random vibrations

Automotive application environments are generally classified by temperature. Table 11-1 indicates the general temperature classifications recognized by the automotive industry, and the intended application. The lower temperature limit for automotive applications is -40°C [104°F].

Besides the requirements of various thermal properties, including flammability, according to the temperature classification, resistance to fuel and engine fluids is a general requirement for all automotive applications. Abrasion resistance is required for PCAs in the vicinity of moving parts and in the engine compartment; flexibility may be required in some applications. For applications exposed to open air, UV stability, hydrolytic stability and low moisture permeability is required.

11.3 Avionics Environment Typical requirements for the conformal coating used in an avionics environment include: resistance to fuel and engine fluids, low flammability and permeability, and good thermal and hydrolytic stability. Specific requirements may include abrasion resistance and nonoutgassing, depending on the applications. There are several avionics environmental distinctions, which should be treated separately

11.3.1 Aircraft on the Ground Ambient ramp air temperatures may range from -46°C to +79°C [-50°F to +175°F]. Any moisture film that collects on the surface will be contaminated by existing air pollutants plus materials that have deposited on the surface of the PCA.

Cleaning and servicing of the aircraft generates numerous pollutants from fumes, spills and leaks. Some of these sources are cleaning solutions, fuel vapors, hydraulic fluids, anti-corrosion sprays, solvents, paint fumes, and paint stripper fumes.

11.3.2 Equipment Outside The Pressure Containment Compartment During Operations The following changes occur in a matter of minutes during the operation of this equipment:

- Temperature changes from +79°C [+175°F] at ground level to -51°C [-59°F] at altitude.
- High humidity at ground level to very low/freezing conditions at altitude.
- 724 Torr [14 PSI] at ground level to 52 Torr [1 PSI] at altitude.

Condensation may form under these conditions, especially on descent because the equipment has been 'cold soaked' at operating altitudes. Frequent transition of temperature and pressure can affect the driving forces of penetration and vapor absorption of contaminants.

11.3.3 Equipment Inside The Pressure Containment Compartment During Operations During the hot summer months sudden temperature changes, 20°C [36°F] or more per second, may occur when the aircraft air conditioning system is turned on. Exposure to blowing condensation occurs when this cold air encounters the warm moist ambient air. During cold weather operations, the reverse actions may occur except the condensation may form on the assemblies, depending on the humidity of the warm air. Pressure changes may occur from 724 Torr [14 PSI] to approximately 362 Torr [7 PSI].

Airborne particles gradually build up on the surface of PCAs. Any condensation, spills or leaks may be potential threats to PCAs.

11.4 Space Environment Radiation in space comes from multiple sources geomagnetically trapped corpuscular radiation of the Van Allen belts, auroral radiation, cosmic radiation, and solar flares. Most radiation experiments are performed under ambient atmosphere conditions but it is believed that effects of radiation (9.15) in vacuum are not as severe as in air due to the lack of oxygen and its role in polymer degradation.

Besides radiation resistance, the conformal coating selected for space environment should likely not outgas in a vacuum environment. Specific requirements of the coating are dependant on the application of the PCAs; high reliability is generally expected.

Table 11-1 Automotive Industry General Temperature Classifications

Class	Application Description	Upper Temperature Limit
I	Passenger Compartment	85°C [185°F]
II	Direct Sun Exposure	105°C [221°F]
III	Engine Compartment	125°C [257°F]
IV	On-engine, in-transmission	150°C [302°F]
V	Brake System Exhaust Manifold, etc	175°C [347°F] 205°C [401°F]

11.5 Medical Environment In a medical environment, conformal coating may be in contact with body fluids, radiation and sterilization media at various temperature ranges. Extremely tight isolation and dimensional tolerances may be required for some medical devices. A special category of medical applications is devices that are implanted in the body cavity that are in long term, intimate contact with body fluids and tissues, which require bilateral compatibility of the coating.

Poly-para-xylelenes (parylenes) are frequently used in devices approved by the FDA for such medical applications. See Appendix J for more information about coating materials for medical applications.

11.6 Geothermal Environment The geothermal exploration industry requires protection of electronic devices in the presence of a 'down hole' environment. This environment may include high temperature 220°C [428°F], high humidity (RH 100%), salt water, crude oil, natural gas, sulfur compounds, caustic high pH solutions, etc.

The conformal coating selected for geothermal applications will likely be resistant to hydrocarbon, acid and alkaline, less permeable to gas and liquid, thermally stable over a wide range of temperature, and dependant on the product, resistant to abrasion.

11.7 Nuclear Biological Chemical Warfare Environment Nuclear Biological Chemical (NBC) environments involve extremely aggressive warfare agents. Coatings should provide protection against these as well as the decontamination agents. Decontamination agents, such as DS2, can be more aggressive then the actual chemical warfare agents. Gas mask voice transmitters are common devices that require protection from these chemicals.

Low permeability to gas, resistance to radiation and specific chemicals is required of the conformal coating in NBC environments. It may be necessary in these cases to use a multi-coating system to provide the necessary protection.

See 9.15 for radiation resistance, for chemical compatibility.

12 LONG TERM RELIABILITY AND TESTING

Long term reliability and testing of conformal coatings on printed circuit assemblies (PCAs) is sometimes defined as how long a coating, when applied on a PCA, yield continuous "failure-free" electrical/functional performance while operating under all intended service environments. Depending on the type of industry, there can be several ways of defining or interpreting long term reliability and testing for reliability. Regardless of the definition, a common primary parameter is the length of time after which a coating is applied to when a failure occurs.

The long term reliability of the coating depends not only on the coating material's properties but on the combination of assembly processes, type of PCA, type of environmental exposures and the duration of the exposure. The contractual requirements (reliability and duration), class type, and the cost of the product will determine the overall level of effort given to address these issues

12.1 Failure Mechanism Failures of PCAs can be attributed to physical failures or defects of the conformal coating during continuous operation and in its intended usage environment. Failures of conformal coating could be the result of inappropriate selection of coating for its intended functions and operating conditions, or improper processing of the coating. If the application and curing procedures were not performed correctly, there may be incomplete development of desired film properties. Even if they may not result in observable faults during inspection, these factors may compromise the long term reliability of the PCAs.

On the other hand, failures of conformal coating could also be indications of contamination and defects on the solder mask or substrate. The failure mechanism of the conformal coating and the conditions of the whole PCA need to be evaluated during failure analysis.

12.1.1 Wear/Abrasion Improper handling, storage or shipping can cause unnecessary contact with coated surfaces. This can result in scratches, scrapes, dents, creases and marred surfaces that can become areas of concentrated stress or contamination ingress. In the case of FC and other PFC based coatings, this usually results in removal of significant areas of the coating.

Breakdown of the conformal coating may be an indication of a design flaw. Design consideration should be given to prevent contact of the coating with other objects in the unit, such as wiring, cases, attaching hardware, or any moveable objects. Internal forced air-cooling can create problems if the airflow is not controlled to prevent venturi type situations. In these cases, an area of high velocity air can rapidly erode coatings due to dust particles.

12.1.2 Loss of Transparency/Discoloration In most cases, marking legends, bar codes, component identification, part numbers, etc. need to be visible through the conformal coating. Loss of transparency and/or discoloration can be caused by excessive exposure to dust or airborne particulates on inherent surface tack, UV light, high temperature, and/or exposure to sulfur or other chemical agents. In some cases, opaque (pigmented) coatings may be desired for security purposes

12.1.3 Cracking Cracks in coatings have several different sources. The presence of cracks can limit the useful life of coatings Because they allow contaminates to penetrate

the coating and represent a breach of coating integrity, the location, length, and depth of the cracks should be evaluated the same as bubbles (13.1.5) Most coatings are true thermal plastics and as such, cracks that form due to cold temperatures will "disappear" as the temperature increases. Even though the cracks are no longer visible, the polymeric links have been broken and contaminates may have penetrated the coating

12.1.4 Loss of Adhesion Several factors affect the ability of a conformal coating to adhere to a PCA These factors include, but are not limited to, cleanliness, compatibility between the coating and other interface material, permeability to moisture, and degree of cure When moisture permeates into the area between the coating and the substrate, a difference in vapor pressure occurs. Changes in temperature and pressure then build up the osmotic pressures and force the coating away from the surface This form of delamination is most noticeable where the coating covers metals because acids may form when there is contamination on the metal surfaces.

Adhesion properties are important to the final product appearance and function. A conformal coating that does not adhere completely to the PCA does not protect that PCA Improper adhesion can lead to blistering, peeling, cracking, mealing, and pop-corning of the conformal coating, especially during thermal and humidity cycling conditions. The risk for adhesion failure is enhanced by the inelasticity of the conformal coating when exposed to mechanical tension.

The adhesion requirement is defined by the agreement between the coating manufacturer, applicator and the end user. The end user and applicator should determine what level of adhesion produces a functional PCA and what test(s), if any, shall be used to determine that sufficient adhesion has been achieved and maintained through environmental conditioning.

Adhesion of conformal coatings can be tested using ASTM 3359 Method B. This test may not be applicable to certain coating types.

12.1.5 Bubbles The presence of bubbles in a conformal coating is a factor of air entrapment, outgassing, mixing and/or application methods. In many cases, this phenomenon cannot be overcome. Bubbles are generally acceptable when their size is less than 50% of the distance between conductors at the location and they do not expose conductor, bridge of lands or adjacent conductor surfaces.

12.1.6 Blistering Blistering is generally a precursor to delamination with one slight difference. It can occur in the coating as well as at the surface coating interface. When blistering occurs in the coating this usually results in a hole or divot in the coating. In any event blistering is a serious problem and should be corrected immediately Blistering is the result of the same situations which cause delamination and should be addressed in the same manner.

12.1.7 Mealing This can be a form of delamination, blistering, and/or adhesion loss, which generally is widespread and can follow a pattern tracing the irregularities of the surface or beginning at the edge of the substrate It is sometimes incorrectly referred to as "orange peeling" because such large sections have delaminated from the surface. It can be caused by improper processes such as too thick of an application, contamination or incorrect curing/drying. Exposure to harsh chemicals or spills can also cause this problem. This situation requires immediate attention and evaluation.

12.1.8 Charring Charring usually occurs due to over heating although it can also result from a severe chemical reaction Reworking, using solder, excessive exposure to UV light, corona discharge, combustion and component overheating are main causes of this problem. Because many forms of contaminates, including carbon, are captured in the coating material and the polymeric links have been damaged, the charred coating should be replaced.

12.1.9 Degradation Degradation is primarily an aging problem due to the types of environmental conditions encountered by coating materials. It is a combination of temperature, moisture, chemicals, abrasion and vibration Coatings can only withstand a certain amount of abuse from the environment before noticeable effects to circuitry operation begin to occur. The nature and amount of harsh conditions each type of coating can handle is variable The resulting effects to the circuitry may also vary

12.1.10 Chemical Attack Incompatibility with chemicals in the operating or end use environment may damage the integrity of the conformal coating. Some chemicals react violently with conformal coatings, causing immediate failure of the coatings, either damaging the PCA at the same time, or leaving the PCA unprotected from other potential threats. Other chemicals may permeate coatings and gradually alter the matrix of the polymers, leaving the coatings at a weakened state, prone to thermal or mechanical failures.

12.2 Accelerated Testing In general, the long term reliability can not be determined in "real-time" conditions. Evaluating long term reliability is usually accomplished by a combination of accelerated environmental test conditions and large number of endurance cycles after which the coating is physically examined using a number of various analytical diagnostic techniques. The coating integrity would be evaluated by conducting visual or microscopic examinations as well as electrical measurements before, during

and/or after exposure to assess percent change. Once electrical failure is identified, it may be correlated to some type of physical evidence that indicates the coating integrity or adhesion has been impacted. This practice is sometimes referred to as accelerated environmental testing. The data generated by using these types of procedures is generally empirical and specific to the performance of the particular coating and the type of PCA being evaluated.

Accelerated life cycle testing, based on expected end use environments, performed on prototype boards and production samples, are capable of demonstrating long term reliability. Reliability testing can help to determine the probability of failure in the field, but not the absolute lifetime of the products.

12.2.1 Test Parameters Unfortunately there are several difficulties with establishing parameters for accelerated testing. Often times, acceleration factors between a set of stress conditions (e.g., temperature cycling from 0 to 100) and mean time between failure (MTBF) are difficult to obtain with precision. Many statistical tools and models are available to aid the user in correlating failure in a test chamber to probability of failure in the field.

The complex synergistic reactions that occur in the field are difficult to duplicate in a test chamber. Therefore the best methodology is to employ a set of test conditions that best emulate the end use environment. For example, the accelerated aging test plan for a PCA that is employed under the hood of a car should include a high temperature condition (as part of a thermal cycle or as a high-temperature soak) as well as vibration. Whereas a consumer electronic product that sits in an office environment does not need to see high temperature conditions or vibration as part of its reliability test plan.

12.2.2 Examples of Tests A number of different tests are available to measure the reliability of a coated PCA. Not every PCA needs to be tested using every condition. A suggested list of test conditions is provided below. Several standards are available that can guide the user in determining a set of test conditions and parameters (e.g., JEDEC, IPC, ASTM, etc.).

- Temperature and humidity test
- Thermal cycling.
- Thermal shock (liquid to liquid, air to air).
- Highly accelerated stress test (HAST).
- Highly accelerated life test (HALT).
- Vibration.
- Salt fog endurance.
- High temperature operating life (HTOL)
- Moisture and insulation resistance.
- Dielectric withstanding voltage
- Flexibility.
- Chemical resistance.
- Humid sulfur environment.
- Mixed flowing gas.

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APPENDIX A
Conformal Coating Comparison Guide

A-1 Due to the numerous variations in conformal coating formulations, the IPC Conformal Coating Handbook Task Group encountered some difficulties in compiling a simple, fair and user-friendly selection guide. Ratings based on the general chemistry type may not accurately reflect the capabilities of each subtype. Rating each subtype may not be possible without revealing individual commercial products, moreover, it will make the guide too cumbersome to use. A consensus was finally reached by listing 5 strengths for each coating type, and 5 weaknesses for each subtype differentiated by cure mechanism. As such, the comparison is general in nature.

5 Strengths of Coating Type	5 Weaknesses of Cure Type
ACRYLIC • Ease of rework • Simple drying process • Good moisture resistance • High fluorescence level • Ease of viscosity adjustment	**Solvent Evaporation** • High VOC potential • Difficult to maintain viscosity • Requires close monitoring of solvent concentration, hence Creates a 2-part scenario • Flammability • High probability of reversion under temperature and humidity stress conditions
	Heat Cure • Cure is dependent on thickness • Component mass affects time and temperature of cure process • Susceptible to cure inhibition • Shrinkage (3% - 10%), potential for damaging fragile (e.g., glass) components • Should be used with caution for low temperature components
	UV Cure • Incomplete cure in shadowed areas • Pungent odor, potential skin irritant • Can become very brittle at higher temperature • Difficult to rework • Type of UV and intensity affect cure

5 Strengths of Coating Type	5 Weaknesses of Cure Type
EPOXY • Useful to about 150°C [302°F] • Harder durometer, abrasion resistance • CTE closer to epoxy PCB substrate • Higher T_g • Good dielectric properties	**Solvent Evaporation** • Higher chloride contamination potential • Process intensive, difficult to maintain viscosity, complex mix ratios • Potential for high stress during temperature cycling conditions • Difficult to rework • High probability of reversion under temperature and humidity stress conditions
	Heat Cure • Cure is dependent on thickness • Component mass affect time and temperature of cure process • Selective coating quality (edge definition) could be impacted • Shrinkage (3% - 10%), potential for damaging fragile (e.g., glass) components • Should be used with caution for low temperature components
	UV Cure • Incomplete cure in shadowed areas • Pungent odor, potential skin irritant • Can become very brittle at higher temperature • Difficult to rework • Type of UV and intensity affect cure
	Catalyzed • Cure inhibition • Short work life • Contamination sensitive • Difficult to rework • Pungent odor

5 Strengths of Coating Type	5 Weaknesses of Cure Type
POLYURETHANE • Good dielectric properties • Good moisture resistance • Solvent resistance • Less reversion potential • Abrasion resistance	**Solvent Evaporation** • Moisture affects cure rate and desired properties • Long complete cure time (up to 30 days) • Health and safety concerns • Potential for high stress during temperature cycling conditions • High probability of reversion under temperature and humidity stress conditions
	Heat Cure • Cure is dependent on thickness • Component mass affects time and temperature of cure process • High VOC potential • Should be used with caution for low temperature components • Reacts violently with presence of water
	UV Cure • Incomplete cure in shadowed areas • Pungent odor, potential skin irritant • Can become very brittle at higher temperature • Difficult to rework • Type of UV and intensity affect cure

5 Strengths of Coating Type	5 Weaknesses of Cure Type
SILICONES • Stable over wide temperature range (in general, 40°C to 200°C) [104°F to 392°F] • Flexible, provides dampening and impact protection • Good moisture, humidity, and UV/sun light resistance • High dielectric strength • Low surface energy to enable effective penetration under components	**Room Temperature Vulcanization (RTV)** • Requires humidity (minimum 20% RH) to cure and only intermittent solvent resistance • Low abrasion resistance • Short pot life • TCE is ~300-350 ppm/°C • If proper house keeping is not followed, there is a potential for cross contamination
	UV Cure • Incomplete cure in shadowed areas • Potential skin irritant • Low abrasion resistance • Only intermittent solvent resistance • If proper housekeeping is not followed, there is a potential for cross contamination
	Catalyzed (Addition) • Low abrasion resistance • Potential for cure inhibition • Adhesion may be difficult • Only intermittent solvent resistance • If proper housekeeping is not followed, there is a potential for cross contamination

5 Strengths of Coating Type	5 Weaknesses of Cure Type
POLY-PARA-XYLELENE C, D, N • Excellent uniformity regardless of part geometry- no pinholes, fillets, or bridging • Chemical inertness/barrier properties- insoluble in organic solvents, acids, or bases, with very low permeability rates • Minimal added mass and low outgassing. • Biocompatibility allows uses in many medical applications. • Low environmental impact process	**Vapor Deposition Polymerization** • Parts are processed by batches in a vacuum chamber, not an in-line process • Masking required for no-coat areas • Coating removal and rework generally requires specific equipment. Abrasion and micro blasting are the more common techniques • Limited UV resistance and operating temperature limit, around 120°C [248°F] in the presence of oxygen • Cannot be doped

5 Strengths of Coating Type	5 Weaknesses of Cure Type
FLUORINATED POLY-PARA-XYLELENE • Excellent uniformity regardless of part geometry- no pinholes, fillets or bridging. • Chemical inertness/barrier properties- insoluble in organic solvents, acids, or bases, with very low permeability rates. • High temperature stability (450°C [842°F]) and increased UV stability. • Low dielectric constant, 2.28. • Low environmental impact process.	**Vapor Deposition Polymerization** • Parts are processed by batches in a vacuum chamber, not an in-line process • Masking required for no-coat areas • Coating removal and rework generally requires specific equipment, abrasion/micro-blasting most common technique. • The coating is deposited at a rate slower than the conventional poly-para-xylelenes. • Requires special deposition equipment different than that for the C, D, and N poly-para-xylelene varieties.

5 Strengths of Coating Type	5 Weaknesses of Cure Type
AMORPHOUS FLUOROPOLYMER • Low dielectric constant • High glass temperature • Low surface energy • Low water sorption • Good solvent, oil and common acid resistance	**Solution Deposition** • Requires special liquids for polymer swelling • Limited solubility which limits film thickness • May require glass temperature anneal • Requires special surface treatment for greatest adhesion • Poor resistance to some acids and alkalines
	Vacuum Deposition • Requires pressure of 10 Torr - 5 Torr [0.193 PSI - 0.097 PSI] or less • May require glass temperature anneal • Requires special surface treatment for greatest adhesion • Poor resistance to some acids and alkalines • Poor abrasion resistance

Note: The strengths and weaknesses of hybrid combinations should be based on constituent components

APPENDIX B
Flow Cup Viscosity Measurement

B-1 There are a large number of flow cup standards for viscosity measurement:

Afnor	Fisher 1, 2	MacMicheal	Shell 1,2,3,4,5,6
BS 4	Ford Cup 3, 4	Mobilometer	SSF
Demmler 1,10	Gardner Holdt Bubble	Norcross 1,2,3,4,5,6	SSU
DIN 4	Gardner Lithographic	Redwood Standard 1,2	Stormer Cyl 100
Du Pont Parlin 7, 10	ISO	Saybolt Universal	Ubbelohde
Dudley	Kreb Stormer	Sayboly Furol	Zahn 1,2,3,4,5
Engler Degrees	Krebs	Sears Craftsman Cup	

A conversion chart for some of the flow cup measurements in seconds and viscosity reading in cP is shown in Table B-1

Table B-1 Conversion Chart for Flow Cup Viscosity Measurements[12]

Viscosity (cPoise)	FORD 4 (CF) (seconds)	AFNOR 4 (CA) (seconds)	DIN 4 (Germany) (seconds)	LCH (France) (seconds)
20	10	12	11	6
25	12	14	12	7
30	14	16	14	0
40	18	20	16	8
50	22	25	20	9
60	25	29	23	10
70	28	32	25	0
80	30	34	26	11
90	33	37	28	12
100	35	40	30	13
120	40	45	34	14
140	44	50	38	15
160	50	56	42	16
180	54	61	45	17
200	58	66	49	18

12 Source Painting guide Y Bailufer - CETIM 1984

APPENDIX C
Troubleshooting Guide

Table C-1 is an example of a troubleshooting guide excerpted from "EMD Training Troubleshooting Guide," Dow Corning, and it may not be applicable to all products. Consult your manufacturer for specific troubleshooting instructions.

Table C-1 Troubleshooting Guide

Topic	Symptoms	Options
Adhesion (lack of)	Adhesive failure, delamination, interface problem (moisture/electrical), inhibition	• Eliminate any contamination (See Inhibition) • Clean/abrade part surface • Use longer cure or heat cure • Increase curing agent level • Treat surface (etching, flame treat, plasma treat) • Use a barrier coating • Select another primer/product • Select self-priming product
Adhesion (unwanted)	Sticking, problem demolding, release problem	• Use release agent • Clean part surface • Cure completely • Freeze to shrink and release • Select another product
Air Entrainment	Bubbles, voids, corona/arcing/electrical failure, moisture, gassing, volatiles	• De-air • Use vacuum impregnation • Replace with new lot of material • Eliminate any contamination causing gassing • Cure at lower temperatures • Select lower-viscosity product • Select product with longer pot life
Air inhibition	Surface tacky/not curing, section too thin to cure, contaminants in air/oven	• Cover with lid or plastic film • Use heat cure • Bake out oven to remove volatiles • Eliminate any contamination
Barrier coating	Inhibition of addition-cure products requiring protective layer on substrate	• Use clear acrylic aerosol spray coating • Use cure accelerator • Use polyvinyl alcohol • Use a primer • Select product with different cure system
Bleed	Migration of nonreactive materials (including silicones, dyes), spreading liquid, relay switches/moving contacts not functioning	• Avoid low-viscosity, nonreactive diluents • Post-bake to complete cure • Avoid contact with solvents • For dye-bleed in mold-making, select a different catalyst • Select higher-viscosity product • Select controlled-volatility product
By-products	Volatiles, corrosion, surface bubbles	• Use longer cure time • Use post-bake or step cure • Avoid confinement of condensation-cure product • Avoid thick application of condensation-cure product • Select controlled-volatility product • Select product with different cure system
Clarity	Translucency, fillers, contamination, incompatibility	• Check shelf life • Replace with new lot of material • Filter material • Select appropriate clear product
Color (Discoloration)	Contamination, incompatibility, thermal/oxidation effects, change in color, color needed	• Blend product to obtain color • Use dye or pigments • Replace with new lot of material • Eliminate any contamination • Avoid incompatible materials • Cure at lower temperatures • Select product with desired color
Confinement	Incomplete cure, slow cure, reversion	• Use longer cure time • Select an addition-cure product that will cure in confinement

Topic	Symptoms	Options
Contamination	Cloudy product, surface or adhesion problems, foreign particles, slow cure corrosion due to moisture	• Eliminate any contamination • Replace with new lot of material • Filter material • See Inhibition • See Primer Quality
Contraction/ Expansion	Coefficient of thermal expansion/ contraction too high, bulging at surface on heating, shrinking/separating/splitting upon cooling, mechanical/hydrostatic stress on heating	• Select product with lower coefficient of expansion • Blend with product with lower coefficient • Select product with high filler content (high specific gravity) • Cure at temperature midway between cycling temperature extremes
Corrosion	Surface reaction, contamination cure by-products, moisture, voids, adhesion problems	• Select noncorrosive-cure product • Select product/primer for maximum adhesion • Avoid products with acid or oxime by-products • Eliminate any contamination
Crazing	Surface cracking, thermal degradation/ oxidation effects, electrical leakage, surface resistance, electrical tracking/ erosion, contamination/moisture, decreased strength, incomplete cure	• Use lower cure temperature • Use longer cure time or heat cure • Select product with higher arc/track resistance • Select product with higher elongation • Select product with higher useful temperature range
Cure (too slow or incomplete)	Long gel or snap time, tacky surface, low durometer, low physical properties, contamination, inhibition, reversion	• Increase amount of catalyst • Accelerate cure with heat • Use cure accelerator for addition-cure products • Select faster curing product • Eliminate any contamination • Select two-part product • Select faster-cure tin catalyst • See Inhibition or Reversion
Cure (too fast)	Short gel or snap time, fast viscosity rise, short pot life, voids/bubbles, poor impregnation	• Blend addition cure product with product with longer pot life • Select slower-cure tin catalyst • Reduce amount of catalyst (down to 5 wt%) • Use pot-life extender • Reduce cure temperature • Freeze material for storage • Select product with longer pot life
Cure (heat cure)	Incomplete cure, tacky surface, thermal degradation	• Check temperature control • Check for sufficient air flow • Clean or bake out any oven spills • Use nonflammable solvent for cleaning
Damming material	Liquid leaking prior to curing, need for liquid Containment	• Use clay, wax, or nonslump adhesive/sealant • Use only noninhibiting materials or noncorrosive alcohol-cure sealants with addition-cure products
Density	Material too heavy	• Select product with lower specific gravity • Blend with product with lower specific gravity • Add low-density fillers
Durometer (too low)	Material too soft, tacky surface, incomplete cure	• Use higher amount of curing agent (Part B) of addition-cure product • Blend with higher-durometer product • Use longer cure time • Use heat cure • Select higher-durometer product
Durometer (too high)	Material too hard, mechanical stress	• Use lower amount of curing agent (Part B) of addition-cure product • Blend with lower-durometer product • Select lower-durometer product
Fillers	Need for flow control, viscosity or strength increase, thermal conductivity, lower cost	• Manufacturer's recommendation for fillers
Flammability (cured material)	Flame rating required	• Select UL-classified material • See product data sheets
Flammability (uncured material)	Low flash point	• Use high-flash-point materials • Use appropriate explosion-proof equipment with lower-flash point materials • See product data sheets • See MSDS

Topic	Symptoms	Options
Fluid resistance	Degradation of physical properties, volume increase/swell	• Select fluorosilicone product • Select material with higher filler content
Gelation (or gels)	Clumps of soft gel, viscosity increase contamination, premature cure, nonuniform cure	• Verify mix ratio and adequacy of mixing • Eliminate any contamination • Check shelf life • Replace with new lot of material • Select product with longer pot life
High voltage problem	Dielectric breakdown, inadequate dielectric strength, voids/bubbles, electrical leakage, corona/arcing/tracking, adhesion problems	• Use vacuum impregnation • Increase insulation thickness • Select product with higher dielectric and/or adhesive strength
Impregnation	Incomplete penetration/fill, voids/bubbles, open interfaces, high voltage problems, corona/arcing/tracking, dielectric breakdown	• Use diluent to lower viscosity • Blend with lower-viscosity product • Use vacuum impregnation • Select product with lower viscosity/longer pot life
Incompatibility	Material separates, milky color, contamination, inhibition, adhesion problems	• Verify adequacy of mixing • Blend only compatible materials • Use proper solvent dispersion technique • Eliminate any contamination • Replace with new lot of material
Inhibition	Incomplete cure, tackiness, uncured liquid, surface inhibition, air inhibition, contact inhibition, contamination, incompatible materials, poor adhesion	• Patch test for compatibility • Prebake to remove volatile inhibiting agents • Use barriers coat • Change the substrate • Use cure accelerator for mild-inhibition for addition cure products • Select condensation-cure product • Avoid addition-cure products
Leakage current	Electrical leakage, volume resistivity, surface resistivity, adhesion problems, high voltage stress, contamination/ moisture/corrosion	• Use primer • Postcure or heat cure to improve cure and adhesion • Use longer cure time on one-part RTV products • Use vacuum impregnation • Clean the substrate • Select product with sufficient electrical properties adhesion • Select self-priming product
Low Temperature	Stiffness/freezing at low temperature	• Select product with low temperature use range, low T_g
Marbling	Incomplete mixing of two-part product, color striations, noncorrosive one-part product precipitates, contamination	• Use longer mixing times • Use longer static mixer • Check shelf life (noncorrosive one-part product) • Eliminate any contamination
Mechanical stress	Material too rigid, high modulus, thermal expansion/contraction, stiffening at low temperature	• Use lower level of curing agent (or Part B) for addition-cure product • Blend with another product • Allow more room for expansion • Select product with lower modulus, lower durometer, higher elongation • Select dielectric gel
Melting point	Softening at high temperatures	• Most conformal coatings are thermoset materials
Military specification	Need MIL/QPL qualification	• Select product with MIL spec • See product data sheets for QPL status
Moisture (excess)	Contamination, milkiness, incompatibility premature cure problems with one-part products, gassing problem with addition-cure products, electrical leakage, corrosion	• Eliminate any moisture contamination • Use proper storage conditions • Prebake substrate
Moisture (insufficient)	Slow cure with moisture cure condensation products	• Use longer cure time • Cure at higher relative humidity
Passivation	Surface sensitivity problem, surface is over-reactive, electrical leakage, corrosion on microelectronic chip surface	• Use surface treatment • Use silane treatment

Topic	Symptoms	Options
Pot Life	Working time too short, premature cure, viscosity rise	• Select product with longer pot life • Blend addition-cure product with product with longer pot life • Use slower catalyst • Reduce amount of catalyst • Reduce storage temperature • Use a pot-life extender
Primer	Adhesive failure, electrical leakage, interface problems	• Select self-priming product • Use a different primer • Use proper primer application technique • Use longer cure time • Use heat cure
Primer quality	Cloudiness, precipitate, poor adhesion, contamination	• Check shelf life • Avoid overexposure to moisture • Replace with new lot of material
Protective coating	Protection against moisture/ contamination electrical leakage, corrosion, surface mechanical damage	• Select conformal coating or resin coating for macroelectronics • Select self-priming product • Use primer
Removal/repair	Replacement/repair of component, repair of damaged material	• Use appropriate stripping agent • Use recommended procedure
Reversion	Depolymerization, reversion from rubber to liquid, thermal degradation	• Minimize confinement with two-part condensation-cure products • Use graduated postbake • Avoid high temperatures • Avoid two-part alcohol condensation-cure products • Select addition-cure or one-part products with higher reversion resistance
Rheology	Material slumping/dripping need flow control/thixtropny	• Use fillers • Blend with nonslump product • Use partial cure (B staging) • Select nonslump product
Settling	Liquid-filler separation	• Mix thoroughly before use • Check shelf life • Select higher-viscosity product
Shelf Life	Premature cure, settling, gels, color change, marbling, cloudiness, precipitate	• Check shelf life • Test material if shelf life is questionable • Select product with longer shelf life • Replace with new lot of material
Solvent dispersion	Product too thick/viscous, solvent impregnation needed, inadequate wetting	• Use appropriate solvent dispersion technique • Use appropriate diluent • Select solvent dispersion product or resin/varnish
Tear strength	Tearing/splitting, inadequate mechanical protection	• Select product with high tear strength • Blend with high-tear-strength product
Thermal degradation (oxidation)	Embrittlement/crazing/cracking, durometer increase reduced elongation weight loss/shrinkage, color change	• Select product resistant to high temperatures or addition-cure product
Thermal degradation (reversion)	Depolymerization, softening/durometer decrease, increased elongation, reversion to liquid	• Select product resistant to high temperatures or addition cure product • Avoid using two-part condensation-cure products
Viscosity (too low)	Material spreading too fast, dripping, leaking prior to cure	• Select higher viscosity or faster-cure product • Blend with higher-viscosity product • Add fillers
Viscosity (too high)	Material too thick, will not spread, poor impregnation, bubbles, voids	• Select lower-viscosity product • Blend with lower-viscosity product • Use diluent • Use solvent dispersion
Weight loss	Volatiles, cure by-products, solvent loss, thermal degradation, deploymerization, shrinkage	• Select addition-cure or controlled-volatility product • Prebake, postbake, or step cure

APPENDIX D
Thermal Analysis

D-1 Glass Transition Temperature (T_g)

The Glass Transition Temperature (T_g) is the temperature at which an amorphous polymer transitions between a super-cooled liquid and its glassy solid, see Tables D-1 and D-2. As a result, amorphous polymers exhibit substantially different physical properties above and below this characteristic temperature. The T_g is strongly dependent on the rate at which the temperature changes through this phase change.

Table D-1 Molecular Interpretation

In glassy state ($T < T_g$)	At glass transition temperature ($T = T_g$)	Amorphous State ($T > T_g$)
• No large-scale molecular motions • Atoms move against restraint of secondary bond forces	• Onset of liquid like motion of long molecular segments • More free volume required	• Large scale molecular motions • Maximized free volume

Table D-2 Measurement Methods

Bulk property measurements	Molecular motion	Thermal Tests

• Volume expansion coefficient
• Heat content
• Refractive index
• Stiffness
• Dilatometry
	• Dielectric loss
	• NMR spectroscopy
		• Thermal Mechanical Analysis (TMA)
		• Dynamic Mechanical Analysis (DMA)
		• Differential Scanning Calorimetry (DSC)
		• Impact
		  • Onset of brittleness
		  • Softening (amorphous polymers)

D-2 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is a technique for determining the T_g of a coating. DSC measures heats and temperatures of transitions, i.e., the amount of energy absorbed or released by a sample as it is heated, cooled, or held at a constant temperature through thermodynamic events such as melting or crystallization. Properties that can be measured via DSC are Glass Transition Temperature (T_g), Melting Temperature (Tm), Heat of Fusion, Degree of Cure, and Crystallization Temperature.

D-3 Thermal Mechanical Analysis (TMA)

Thermal Mechanical Analysis (TMA) is a technique for determining CTE. Properties that can be measured via TMA are CTE and T_g.

D-4 Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) is a technique for determining CTE and T_g. DMA measures changes in the mechanical (viscoelastic) behavior (modulus and damping) of polymeric materials as a function of temperature, time, frequency, stress, or combinations of these parameters. Film, fiber, and bulk material samples can be measured. The DMA also operates in a constant force mode to perform TMA Testing. Properties that can be measured via DMA are Elastic Modulus, Flexural Modulus, Poisson's Ratio, T_g, CTE, Creep/Recovery, Gel Point, and Heat Deflection.

D-5 Thermal Gravimetric Analysis (TGA)

Thermal Gravimetric Analysis (TGA) is a technique for determining weight loss as a function of temperature. Properties that can be measured via TGA are decomposition temperature, volatile content and, filler content.

APPENDIX E
Relative Humidity

E-1 Relative humidity (RH) is a ratio, and to better understand its impact a molecule count is needed. At 50% relative humidity and 25°C [77°F] there are about 4×10^{17} molecules of water per cubic centimeter

As humidity levels increase, microscopic water droplets begin to form in the atmosphere (known as nucleation). This can occur as low as 40% RH. These droplets combine with various pollutants to form suspended acids The U S. EPA has determined half of the haze in the Northeast United States, on warm, humid summer days, is due to suspended acids. Humidity also plays a very important role in the chemistry of particles.[13]

E-2 Critical Relative Humidity (CRH) is defined as the temperature and humidity level at which a material will begin to absorb water vapor from the air. Because the dry deposition of pollutants on surfaces is a complex mixture there is no set point for this to occur It is possible for isolated locations to absorb water vapor with humidity and temperatures as low as 20% and 25°C [77°F], respectively. This random situation is capable of causing intermittent apparently unrelated failures in the field. Moisture captured by surface deposited materials remains for extended periods even when warm dry air is applied.[14]

The relative humidity level must drop well below the CRH (as much as 20% to over 30%) to completely remove the moisture. For example the humidity must drop to 43% to completely dry out NaCl particles. See Table E-1 for additional examples.

Table E-1 Critical Relative Humidity (CRH) For Several Inorganic Compounds[15]

	Compound	Temperature (°C)	Relative Humidity (%)
1	$LiCl\ H_2O$	20	15
2	KF	100	22.9
3	NaBr	100	22.9
4	$CaCl_2.6H_2O$	24.5	31
5	$CaCl_2.6H_2O$	5	39.8
6	$(NH_4)HSO_4$	24	40
7	NH_4NO_3	24	65
8	KBr	100	69.2
9	NaCl	20	75
10	KCl	80	78.9
11	$(NH_4)_2SO_4$	24	81
12	KBr	20	84
13	KCl	0	88.6
14	NaF	100	96.6
15	$(NH_4)_3H(SO_4)_2$	25	69
16	$NaNO_3$	25	74.3
17	$NaCl\text{-}NaNO_3$	25	68
18	NaCl-KCl	25	72.7
19	$NaSO_4$	25	84.2
20	H_2SO_4	25	5

13 U.S. Environmental Protection Agency, "National Air Quality and Emissions Trends Report," 1998, 454/R-00-003
14 Douthit, D.A. "Avionics Systems Reliability, and Harsh Environments," May 2001
15 Finlayson-Pitts, Barbara, "Chemistry of the Upper and Lower Atmosphere," *Academic Press*, November 1999
Schweitzer Philip A., P.E. "Atmospheric Degradation and Corrosion Control," Marcel Deker Inc., September 1999.
Tegehal, Erik. "Reliability Verification of Printed Board Assemblies A Critical Review of Test Methods and Future Test Strategy," August 1998

APPENDIX F
Time of Wetness

F-1 ISO Specification 9223 refers to the "Time of Wetness" as any RH ≥80% when the temperature is above 0°C [32°F]. The Swedish Institute of Corrosion has further quantified this by creating a time of exposure chart as shown in Table F-1 This classification shows that in temperate and warm climate zones, 30 to 60% of the time the relative humidity of the outdoor environment is higher than 80% when the atmospheric temperature is above 0°C [32°F]. In tropical climates, the humidity is generally higher

The "wetness" referred to is the formation of a thin aqueous film on surfaces. The reason 80% RH was chosen is because at this level the film will reach a thickness of >5 water molecules on clean smooth surfaces. When this thickness is reached, the film will begin to chemically act as bulk water. The 5 molecule thick layer can be formed as low as 60% RH on rough and/or contaminated surfaces [16]

Table F-1 Time of Wetness[17]

	Hours/ Year	% of Year	Example of Occurrence
t_1	<10	<0.1	Indoor air with climate control.
t_2	10-250	0.1-3	Indoor air in normal rooms for living or working conditions.
t_3	250-1000	3-10	Indoor air storage rooms
t_4	1000-2500	10-30	Indoor air in some production rooms. Outdoor air in cold zone, dry zones, and parts of temperate zone.
t_5	2500-5500	30-60	Outdoor air in parts of temperate zone and parts of warm zone. Indoor air in animal houses.
t_6	>5500	>60	Outdoor air in tropical zone. Indoor air in greenhouse.

16 Schweitzer, Philip A. P.E., "Atmospheric Degradation and Corrosion Control," Marcel Deker Inc., September 1999.
17 Swedish Corrosion Institute, "Corrosion of Electronics," Bulletin No. 102, Stockholm, Sweden, 1991

APPENDIX G
Atmospheric Particulates

G-1 Submicron particles are the third and final stage of the chemical life cycle involved in industrial pollution. The first, generation of gaseous reactive agents (NO_x, SO_x, and O_3), is followed by the second, creation of liquid acids (H_2SO_4, HNO_3, and HCl) All three stages represent a threat to circuitry reliability Selecting a coating capable of resisting this combined hostile environment is necessary. Two papers presented in October 1999 during the Electrochemical Society International meeting in Honolulu provide a very good overview of problems with submicron dust· Reliability of Electronics in Harsh Environments: Electrical Leakage and Corrosion Caused by Hygroscopic Pollutant Particles, R.B. Comizzoli, R.P. Frankenthal, G.A. Peins, L.A. Psota Kelty, D.J. Siconolfi, J.D Sinclair, Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974, USA

G-2 In many parts of the world, soft coal is the primary energy source. Combustion of soft coal produces sulfur dioxide, which oxidizes in the atmosphere to form sulfuric acid and other oxidized sulfur-containing molecules. When electronic equipment and devices are contaminated with particles derived from these gases, subsequent exposure to atmospheric moisture can cause failure due to electrical leakage and arcing in the presence of electric fields

G-3 The most important components of the environment with respect to degradation of electronic devices are particles and water vapor Most of the mass of particulate matter in the atmosphere exhibits a bimodal distribution. Particles 2.5-15 m are largely derived from natural materials and are usually called coarse particles, while particles 0.1-2.5 m, usually called fine particles, are largely derived from anthropogenic sources. The combined mass of fine and coarse particles in the atmosphere is frequently referred to as total suspended particulate (TSP). In the U.S. typical TSP levels are 30-40 $\mu g/m^3$ outdoors and 5 $\mu g/m^3$ indoors. Typical sulfate levels are 4-6 $\mu g/m^3$ outdoors and 0.6-0.8 $\mu g/m^3$ indoors. For the new work reported here, TSP levels in excess of 200 $\mu g/m^3$ have frequently been measured outdoors in many parts of Asia The sulfate portion of this mass is frequently in excess of 15 $\mu g/m^3$. Indoor TSP concentrations are frequently in excess of 30 $\mu g/m^3$.

G-4 Coarse particles form predominantly by abrasion processes, e.g., construction activity or the action of wind on soils. The main source of fine particles in populated areas is fossil fuel combustion, though volcanic and geological activity can also contribute. Due to their different origin, coarse particles tend to have a lower fraction of water-soluble ionic components (5-20%) than fine particles (25-50%), excluding H^+, OH^-, and CO_3^{2-}. With any particle, the higher the fraction of water-soluble ions, the higher is the corrosivity As a result, fine particles are more corrosive than coarse particles. Key to the corrosive behavior of fine particles is their critical relative humidity (CRH) CRHs at 24°C [75°F] of some of the major ionic compounds found in fine particles in most urban environments are: NH_4HSO_4, 40%, NH_4NO_3, 65%; NaCl, 75%: $(NH_4)_2SO_4$, 81%. The electrolyte films that form on surfaces contaminated with fine particles when they absorb moisture are corrosive to many metals and can lead to electrolytic corrosion or leakage currents when an electric field exists between conductors.

G-5 The indoor concentrations of fine particles in buildings with central air handling systems can range from 20-50% of the outdoor concentrations, depending on:

1. The efficiency of air filtration systems, including both building systems and equipment filters;
2. The rate at which outdoor air is brought into the building; and
3. Indoor sources, e.g , smoking or human activity.

G-6 Concentrations within homes, sheds, and utility huts can range from 20-75% of the outdoor concentration due to:

1 The penetrability of particles through air-leakage pathways or open doors or windows;
2 The absence of efficient particle air filtration; and
3 Indoor sources like those mentioned above, as well as aerosols derived from liquid processes.

G-7 On PCBs, the absorption of moisture by deposited particles or other ionic contaminants may result in the formation of an electrolyte around electrical leads Bridging of leads can result in leakage currents. The current may lead to soft errors or cross talk If the electrolyte extends over a defect in the covercoat and the defect sits above a conductor operating at a different voltage from that on the lead, arcing can occur between the lead and the conductor. Typically, the leakage current

increases approximately exponentially with RH Covercoats can be effective in preventing hazardous leakage currents. However, device leads and electrical contacts are not usually covered by covercoats.

G-8 The maintenance of the RH in electronic equipment locations below 60% minimizes the risk of hazardous leakage currents For conductive contaminants (e g., graphitic carbon or metallic dust) high leakage currents may occur even at low RH. The electrical leakage of dust from the more polluted environments of the world tends to be significantly higher at a given RH than dust from the U.S. In addition to electrical leakage and arcing, dust and other ionic contaminants can lead to direct corrosion of metal conductors and ultimately to open circuits. A water-soluble corrosion product may also migrate to the negative conductor, where it can be reduced to form a metallic deposit that grows toward the positive conductor, eventually forming a short circuit. In some situations, an arc may occur. Severe arcing can pyrolyze PCBs to form conductive carbon bridges. In the absence of appropriate limitation of current, a fire could result. Again, the combination of contamination, moisture, and bias are required.

G-9 To minimize leakage currents and corrosion in field operations, it is essential that:

1. Covercoats are defect free, which can be evaluated by appropriate dust exposure tests;
2. Design rules and specifications with respect to bond pad and line spacings are strictly followed; and
3. The environment is maintained within design specifications.

G-10 To evaluate the effect of environmental interaction on the reliability of electronics, the components of the environment that need to be considered are:

1. Corrosive gases derived primarily from fossil fuel combustion;
2. Coarse particles (>1 µm) formed by erosion of soil and minerals or flaking of biological materials; and
3. Fine particles (<1 µm) produced from corrosive gases through chemical and physical processes that occur in the atmosphere

G-11 In recent years, ionic contamination from fine particles has been a common cause of field failures. The increased use of forced-air cooling, brought on by increasing power densities in electronics, has caused up to a 100-fold increase in the deposition rate of fine particles to critical component surfaces. See Table G-1 for Deposition Rates for Particles. In many urban indoor environments, the mass concentration of these particles and their arrival rate at surfaces are comparable to the mass concentration and arrival rate of corrosive gases. Fine particles play the decisive role in the corrosion of electronics because of their higher concentration indoors (due to low filtration efficiencies for fine particles) and because of their greater content of soluble ions compared to coarse particles. [18]

G-12 It is now possible to measure particles down to 0.002 µm [7.9 x 10^{-5} mil] in diameter. This has created a new category for particles called ultra-fine particles (from 0 002 µm to 0.01 µm [7-9 x 10^{-5} mil to 3.9 x 10^{-4} mil]). Counting these particles with the others gives a TSP (Total Suspended Particles) count for polluted urban environments of up to 10^{5} power of particles per cubic centimeter.

G-13 Particulates in the air are very seldom composed of one material. When CRH (Refer to 11 1.2 Humidity) is reached particles will begin to grow quite rapidly. This moisture allows adsorption plus absorption of organic and inorganic materials. A typical particle may consist of $(NH_4)_2SO_4$, Na_2SO_4, water, with organic acids Because lowering the humidity can raise the pH factor of particles it has been estimated the pH factors of particles in southern California can be 0.2 or less.[19]

Table G-1 Deposition Rates for Particles

Particle Size (Micron)	Deposition Rate (per ft² per second)
0 01 to 0.1	2 x 10^6 to 2 x 10^9
0.1 to 1	2 x 10^3 to 2 x 10^6
>1	20 to 2 x 10^3

Indoor deposition rates will vary from 20% to 80% of the outdoor rates. These measurements done by Bell Laboratories, do not include ultra-fine particles.

18. Corrosion and Protection of Metals in the Presence of Submicron Dust Particles
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R P Frankenthal, C A. Jankoski, D.J Siconolfi J.D Sinclair, Lucent Technologies Bell Labs Innovations, Murray, Hill N J , USA
M.Unger, M Statmann, Erlangen University Erlangen, Germany
19 Li et al , 1997

APPENDIX H
Airborne Contaminants

H-1 Atmospheric pollutants pose a serious threat to electronic circuitry because of the very complex and complicated synergistic chemistry involved which generates numerous ionic and hygroscopic microscopic compounds. These pollutants transform through three chemical stages. The first is the generation of very reactive gaseous agents (NO_x, SO_x, O_3, H_2O_2, NH_3, H_2S). The next stage is the creation of liquid acids (H_2SO_4, HNO_3, HCl). The final stage results in submicron hygroscopic ionic particles (NH_4HSO_4, NH_4NO_3, $[NH_4]_2SO_4$) plus numerous others. Unfortunately, all three stages are present in the atmosphere at any given time. Which stage is predominate depends on the time of year, temperature, humidity, local weather conditions, effectiveness of environmental control methods, and the length of time the circuitry has been in use. All three stages require the presence of moisture, which will cause the chemical reactions that can/will degrade electronic reliability.

H-1.1 The U.S. Environmental Protection Agency (EPA) measures contaminates under three different conditions. The first is ambient air. Every hour a sample of one cubic meter of air is tested to determine the amount of ozone, SO_2, NO_2, plus particulates that are 10 µm [0.39 mil] or less in size.

H-1-2 The second is called dry deposition. Dry deposition of contaminates accounts for 60% to over 90% of the removal of pollutants from the atmosphere. Deposition refers to the method of removal or transfer. Any form of removal that does not involve the depositing of contaminated moisture by gravity is "dry deposition." These are measurements of the amounts of SO_2, HNO_3, SO_4, NO_3, plus numerous organic and inorganic compounds deposited on a flat surface in the form of particles less than one micron in size. Measurements can be by mass (µg per square surface area) or by count (particles per square surface area).

H-1.3 The third method is called wet deposition. The following contaminates are measured in mg or µg per liter of rain water; sulfates (SO_4^{2-}), nitrates (NO_3^-), calcium (Ca^{2+}), ammonium (NH^+), chloride (Cl^-), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+). These are the primary contaminates that are in acid rain. The pH factor for rain water in the United States will vary from 6.0 to 4.2 (per 1998 data available through the National Atmospheric Depository Program).

H-2 Ambient Air

The mean average annual levels for ambient air pollutants in the worst locations are shown in Table H-1.

Table H-1 Ambient Air Pollution Levels

Pollutant	Contamination Level	Location
SO_2	17 ppb	Kentucky, Pennsylvania, and Ohio
NO_2	40 to 43 ppb	New York City and Los Angeles
O_3	140 ppb	Riverside, California (The number of sites above 100ppb are too numerous to list)
PM10	60µg/cubic meter	Las Vegas, Nevada (Numerous sites in the 30 to 40µg range)

Note: Ozone amounts vary a great deal so the standard measurement is the average reading during any given 8 hour period.
Note: PM10 = particles 10 µm [0.39 mil] or less in size (mainly carbonaceous particles) [20]

20 U.S. Environmental Protection Agency, "National Air Quality and Emissions Trends Report," 1998, 454/R-00-003

H-3 Dry Deposition

These are measurements taken over wide rural areas, in this case the Ohio River Valley. The deposition amounts may vary considerably in urban areas. The measurements in Table H 2 are in Kg/Ha.

Table H-2 Dry Deposition Measurements[21]

	SO_2	HNO_3	SO_3
Winter 97	4.28	1.32	0.12
Spring 97	2 52	1.46	0.21
Summer 97	1.11	1.10	0.22
Fall 97	1 78	0.73	0.12
Totals Kg/Ha	9.69	4.61	0.67
Totals µg/cm²	97	46	6.7

H-3.1 AIRMoN-dry Data Summaries[22] The data presented in the links below represent the best estimates currently available from the AIRMoN-dry network. They are made available with a strong recommendation for caution in their use. The science of dry deposition continues to evolve The data presented here is expected to be modified as more is learned about the processes that control dry deposition

The AIRMoN concentration sampler is a three-element filterpack, with a leading teflon filter to remove particles, a middle nylon filter to extract nitric acid vapor, and a final doped cellulose filter intended primarily to sample sulfur dioxide. An inlet tube is used to impose a small amount of heat on the incoming air stream, to protect against liquid formation on the filters in periods of high humidities. There is no doubt that this influences the measurement of ammonium nitrate. In practice, any temperature change imposed on collected ammonium nitrate particles will cause some change in the sample, so that any long-term accumulative measurement of related species (such as that reported here) will be susceptible to error because of the effects of the diurnal cycle in air temperature. Tests of the AIRMoN sampling system indicate that particulate ammonium nitrate deposited on the teflon filter is incompletely disassociated with minor consequences on the measurement of nitric acid vapor and of sulfur dioxide, but with major influence on the measurement of nitrate on the doped cellulose filter For this reason, measurements of nitrate reported here are considered to be unreliable.

Tests indicate that the values associated with nitric acid vapor are underestimates, on the average by 25%. The values listed should be increased accordingly, to correct for this error (due to deposition on the walls of the inlet tube).

Deposition velocities tabulated here are derived using a multi-layer numerical model, driven by field observations of selected key variables (such as wind speed, the standard deviation of the wind direction, surface wetness, incident solar radiation, temperature, humidity, plant species distribution, etc.) It is estimated that these deposition velocities might be in error by as much as 30%.

Weekly average deposition rates are computed as the product of the weekly average deposition velocities and the weekly average concentration, thus omitting consideration of a correlation term that can be significant when air concentrations display a consistent and significant diurnal cycle.

21 U.S Environmental Protection Agency, "National Air Quality and Emissions Trends Report," 1998 454/R-00-003
22 The following information was obtained from the National Oceanic and Atmospheric Administration (NOAA) website, www.arl.noaa.gov/research/project/airmon data.html.

H-4 Wet Deposition[23]

The ion measurements in Table H-3 represent the highest levels of contaminates and their locations

(Source: The National Atmospheric Deposition Program web site: nadp.sws.uiuc.edu/isopleths)

Table H-3 Highest Levels of Wet Deposition[24]

Contaminant	Level	Location
SO_4	2.6 mg/L	Columbus/Akron OH
NO_3	2.3 mg/L	Buffalo, New York
Cl	1.14 mg/L	East Coast of Maine
Na	650 µg/L	East Coast of Maine
NH_4	0.60 to 0.66 mg/L	S Dakota, Nebraska & Kansas
Ca	0.67 to 0.68 mg/L	SW Texas and Salt Lake City
Mg	116 µg/L	Sacramento, California
K^+	112 µg/L	Western Kansas

H-5 Concentration of selected gaseous air constituents (ppb) in the United States[25]

Because measurement of gases is done in ppb (parts per billion) and is a ratio a false since of security can be created. In a dry standard atmosphere (760 Torr [14.70 PSI] pressure) 1 ppb equals 2.46 x 10^{10} of molecules per cm^3. Multiply 24.6 billion by the total count in Table H-4 (about 200). Even this is not quite accurate because these numbers represent an arithmetic mean. Spikes in these numbers can cause these counts to climb by as much as a factor of 20. If you discount the inert nitrogen in the atmosphere (about 80%) the ratio between oxygen, moisture, and contaminates becomes clear. [26]

Many reactive gases (SO_2, H_2S, Cl_2, HCOOH, O_3, NH_3, NO_2, and H_2O_2) can combine with moisture creating acids (H_2SO_4, HNO_3, and HCl) and corrosive particles (NH_4HSO_4, NH_4NO_3, $[NH_4]_2SO_4$). These chemical reactions may break down polymeric chains leading to micro-flaws in coatings, which become delaminations. These gases as well as moisture are always present and will cause a general degradation of coatings plus other polymers and metals over extended periods of time. No one knows how long this process takes.[27]

Table H-4 Concentration of Selected Gaseous Air Constituents in US

Gas	Outdoor	Indoor
O_3	4 - 42	3 - 30
H_2O_2	10 - 30	5
SO_2	1 - 65	0.3 - 14
H_2S	0.7 - 24	0.1 - 0.7
NO_2	9 - 78	1 - 29
HNO_3	1 - 10	3
NH_3	7 - 16	13 - 259
HCl	0.18 - 3	0.05 - 0.18
Cl_2	<0.005 - 0.08*	0.001 - 0.005
HCHO	4 - 15	10
HCOOH	4 - 20	20

* Corresponding to 5 wt% HCl.

23 Taken from the National Atmospheric Deposition Program website, nadp.sws.uiuc.edu/isopleths

24. U.S. Environmental Protection Agency, "National Air Quality and Emissions Trends Report," 1998, 454/R-00-003

25 Schweitzer, Philip A., P.E. "Atmospheric Degradation and Corrosion Control," July 1999.

26 Douthit D.A., "Avionics Systems, Reliability, and Harsh Environments," May 2001

26 Finlayson-Pitts, Barbara, "Chemistry of the Upper and Lower Atmosphere," Academic Press, November 1999

27 Douthit D.A., "Avionics Systems, Reliability, and Harsh Environments," May 2001.

H-6 Indoor Dry Deposition

In 1986, a study was done on the amount of pollutants and the resulting corrosion to electronic metals (silver and copper) that would occur in indoor environments in Japan and other Southeast Asian countries. Table H-5 is a sample of the most and least amounts of pollutants collected. It is very apparent that location is a major factor in contamination rates.

Table H-5 Indoor Pollution Levels in the Far East

Pollutant	Location	With Air-conditioning	No Air-conditioning
SO_2	Tokyo	58 μg/cm² (staff room, urban)	39 μg/cm² (chemical lab, urban)
SO_2	Bandung	0.23 μg/cm² (measuring room, rural)	0.54 μg/cm² (hydrometallurgy lab, rural)
NO_2	Tokyo	211 μg/cm² (staff room, urban)	129 μg/cm² (computer room, rural)
NO_2	Bangkok	0.08 μg/cm² (essential oil lab, urban)	0.28 μg/cm² (farm house, rural)
Cl (gas)	Bandung	13.7 μg/cm² (measuring room, urban)	38.9 μg/cm² (metallurgy lab, urban)
Cl (gas)	Singapore	0.05 μg/cm² (library, urban)	0.06 μg/cm² (living room, suburban)

Note: All amounts are μg/cm² per year.[28]

Moisture represents the most common and critical atmospheric contaminate. It is the catalyst in over 90% of all corrosion and electrochemical migration problems. Coatings are permeable by moisture in either liquid or vapor form. Sulfates, nitrates, chlorides, and sodium are very hydroscopic and will combine with water, each other, and other compounds to form harmful chemicals.

Above 80% relative humidity droplets form in the atmosphere that contain sulfuric acid, nitric acid, hydrochloric acid, ammonia nitrates, and ammonia sulfates among other compounds. Sulfates will not evaporate and will build up on surfaces. Also a layer of moisture will form on the surface of metal between 5 and 10 molecules thick. This layer is very contaminated and can cause a great deal of damage.[29]

H-7 Ozone

Ozone (O_3) is a very reactive gas. It has a short life expectancy when it comes into contact with other materials. It is capable of reacting with many forms of organics, including polymers and elastomers. Most polymers have additives to prevent direct attacks from ozone.

When moisture, organic compounds and other reactive gases are combined with ozone a wide variety of chemical reactions can occur. Some of them are capable of causing a break down in polymeric chains and or cross linkage.

Atmospheric ozone only occurs during the day, primarily in the afternoon and early evening. Levels from 100 >200 ppb are present in many urban environments. Ozone can also be generated by electrical sparks, such as those caused by motors or generators with brushes.[30]

H-8 Hydrocarbon Gases

There are currently 151 organic compounds being monitored in the air. Of these over 40 are polarized organic acid. Individually the amounts are not large but when the total amount is combined, the result is 500 to 1000 μg/m³ in a typical urban environment.

Organic compounds in the air are a major source of halogens (fluorine, bromine, chlorine, and iodine). Most are hygroscopic and combine with moisture on suspended particles in the air as well as surfaces. This increases the ability of surfaces to create aqueous layers in high humidity conditions. Organic compounds are also very sticky. This makes deposited pollutants coated with them difficult to remove.

These organic compounds also react with OH molecules to create H_2O_2. They also react with O_3 and other gases. By themselves, organic gases do not pose a threat to electronic circuitry but they can break down and generate other compounds which are harmful. The synergistic relationships between reactive gases, acids, and particles is an extremely complex and continuous process.[31]

28. Pecht, Dr. Michael, and D.A. Douthit, "Contamination of Electronic Assemblies," CRC Press, June 2002
29. Douthit, D.A., "Avionics Systems, Reliability, and Harsh Environments," May 2001
30. Schweitzer, Philip A. P.E., "Atmospheric Degradation and Corrosion Control," July 1999
31. Finlayson-Pitts, Barbara, "Chemistry of the Upper and Lower Atmosphere," Academic Press, November 1999.

APPENDIX I
Simulated Acid Rain Test

I-1 Rain will be acidic even without the influence of man. Natural sources, CO_2, volcanoes, fire, even bacteria generate gases which cause rain to be acid (pH 5.2 >6.0). In fact, sulfates and nitrates are a necessary part of the fertilization process. It is impossible and unwise to eliminate them. The problem stems from man made sources of combustion and other VOCs (Volatile Organic Compounds) released into the air. A complex series of chemical reactions begin when these gases are combined with moisture and ultra-violet light. Ozone (O_3), sulfates (SO_x) and nitrates (NO_x) are the primary sources of "acid rain" (pH <5.0).

The chemical reactions require up to 48 hours and result in a 'mature' acid content consisting of 63% sulfuric acid (H_2SO_4), 31% nitric acid (HNO_3), 6% hydrochloric acid (HCl). Because the amount of acid depends on exposure to sunlight (UV), moisture, and warm temperatures there is more acid generated in the summer then in the winter. The EPA has determined 50% of the haze seen in the north eastern United States during hot humid (>80% RH) days is composed of acids. As dew point is approached these microscopic acidic water droplets begin to collect and form clouds, drizzle, mist and rain. The harder and longer the rainfall the less the amount of acid it contains as it is "washed" or "scavenged" from the air.

Fog, drizzle, and mist can be extremely acidic (a pH of 1.5 has been measured from fog in West Virginia). Nitric and hydrochloric acids will evaporate at about the same rate as water. Sulfuric acid does not evaporate and is considered a particulate even though it is suspended in moisture. Ammonia (NH_3) will not combine with moisture but it does combine with sulfuric and nitric acids to form sulfates (NH_4HSO_4 / $(NH_4)_2SO_4$) and nitrate (NH_4NO_3) submicron size particles which can be acidic or base will be deposited as dust. These ammonium sulfates and nitrates will absorb moisture generating both anions and cations. These ions can cause leakage currents, temporary short circuits, and dendritic growth.[32]

The EPA has created a formula for "acid rain" for use in testing: Simulated acid rainwater per the U.S. Department of Commerce National Bureau of Standards Special Publication 260-106. Reference Material 8409 and Standard Reference Material 2694.

Table I-1 Acid Rain Formula for Testing Purposes

pH	3.6
Specific conductance, uS/cm	130.0
Acidity, meg/L	0.28
Fluoride, mg/L	0.1
Chloride, mg/L	1.0
Nitrate mg/L	7.0
Sulfate, mg/L	11.0
Sodium, mg/L	0.4
Potassium, mg/L	0.1
Ammonium, mg/L	1.0
Calcium, mg/L	0.05
Magnesium, mg/L	0.05

There is no mention as to the form these chemicals might be in, i.e., nitrates - NO_2, NO_3, or sulfates - SO_2, SO_3, SO_4, or compounds such as sulfuric acid, nitric acid, hydrochloric acid, sodium chloride, sodium nitrates, sodium sulfates, ammonium nitrates, or ammonium sulfates plus other combinations. All of the above chemicals are created in the atmosphere when combined with ozone (O_3), sunlight (UV rays), and moisture (water vapor and droplets). To further complicate matters most of these compounds will deposit on surfaces without liquid water (rain or condensation) as a carrier (known as dry deposition).[33]

There are several problems which will effect the long term reliability of coated circuitry in harsh environments. The coatings can be damaged due to osmotic pressures and chemical reactions when moisture is combined with various pollutants. This results in flaking, discoloration, blistering, and finally delamination as the polymeric links are broken down.

32 Finlayson-Pitts, Barbara, "Chemistry of the Upper and Lower Atmosphere," Academic Press, November 1999.
33 Douthit, D.A., "Avionics Systems, Reliability and Harsh Environments," May 2001

When the moisture combined with pollutants reaches the board surface, oxidation and corrosion of metal circuitry and component leads will begin. The bonding of the coating will tend to break down at the interface of the metals to the coatings. These are problems that can occur when there is no power applied to the circuitry [34]

When power is applied, under these circumstances, electrochemical migration can begin leading to dendritic growth. To effectively determine the ability of the coating to filter pollutants SIR testing can be done while the coated circuit is exposed to a high humidity polluted atmosphere with and without power applied.

34 Schweitzer Philip A. P.E "Atmospheric Degradation and Corrosion Control," July 1999

APPENDIX J
Coating for Medical Applications[35]

J-1 A surface coating can be used to modify and enhance critical surface characteristics of selected medical components and devices, thereby helping to satisfy a variety of performance requirements. The following is a discussion of some of the primary categories of application for medical coating applications, and also a review of issues that can be addressed to determine the suitability of this process for individual applications.

There are a number of surface modification functions that can be accomplished by conformal coatings on PCAs for medical applications These include:

- Isolation of surfaces from exposure to body tissues and fluids and vice versa
- Provision of selective or overall electrical insulation
- Improvement of lubricity or slipperiness
- Stabilization/consolidation of surfaces by immobilizing micro-particles
- Sealing of surface micro-porosity so as to restrict the entrapment of contaminants
- Mechanical stabilization of very delicate structures
- Function as an intimal surface that promotes tissue growth

Whatever the specific medical application, a coating should be able to achieve the desired surface modification without adding bulk mass that could adversely affect form, fit, or function.

Although conformal coatings have been widely used in industrial, automotive and aerospace applications, a special level of sophistication is required for medical coating processes Consideration begins with selection of the coating material, followed by preparation of surfaces to be coated, and the actual coating process There are a number of important issues to be considered when selecting a conformal coating for medical electronics application. These include:

- ***Biostability/Biocompatibility*** – The bilateral long-term compatibility and nonreactive relationship between the coating and body fluids and tissues
- ***Freedom from cure byproducts*** – A medical coating should not contaminate the substrate with outgassing or byproducts from catalysts, solvents, or plasticizers. It should not undergo any chemical interaction with the substrate to which it is being applied, or produce toxic byproducts that could be harmful to the patient or the function of the item being coated.
- ***Hydrophobicity*** – What is the ability of a surface to be wetted or not.
- ***Cure and operating temperatures*** – Should be within the performance range of the device or substrate.
- ***Cure forces*** – Should not degrade or distort the underlying structures
- ***Conformability to highly variable surface geometries*** – A coating should provide effective isolation of all surfaces, including under components, hidden areas, crevices, etc , without bridging or pooling. The coating should be able to accomplish this at all magnitudes of size from macro to micro.
- ***Finished thickness*** – A coating may need to meet extremely tight dimensional tolerances while providing uncompromised, physical, chemical, or electrical protection for the substrate with coverage free of voids and pinholes.
- ***Mechanical loading*** – A coating should function without significantly altering the desired mechanical characteristics or responses of the device
- ***Resistance to flaking*** – A coating should be adequately robust and adherent to prevent unwanted flaking from the substrate.
- ***Sterilizability*** – Properties should not degrade when subjected to an appropriate sterilization media

J-2 Medical Coating Applications

Biomedical coating applications are found in two basic categories: short-term (for example, expendable surgical items), and long term (such as prosthetic hardware and various implants).

35 Courtesy of Lonny L. Wolgemuth, Specialty Coating Systems (SCS)

Some simple, short-term applications may require surface isolation only, and this can be accomplished by a coating that creates a benign barrier between the device and organic tissue. However, a coating may also be required to provide one or more secondary properties as well, such as lubricity or dielectric protection.

Long-term medical coating applications may have similar performance requirements, with the ability to perform as intended for an extended period of time. A biocompatible coating may be required to serve other functions as well, such as to promote tissue growth or avoid thrombus generation.

Here is a list of common medical objects that may require conformal coating. A brief review of the principal coating functions for each of these applications is provided.

J-2.1 Short Term or Temporary Applications

- ***Medical Seals*** – A coating is used to eliminate tackiness, supplement mechanical strength, provide dry film lubricity, and achieve chemical isolation.
- ***Pressure Sensors*** – Sensor coating entails protection of delicate, sensitive elements without mechanically loading the transducing media or otherwise interfering with the device function.
- ***Guide Wires*** – The coating functions to increase lubricity, and to isolate wires from corrosive biofluids.
- ***Catheters*** – Coating increases lubricity, and isolates surfaces from corrosive biofluids.
- ***Ultrasonic Transducers*** – Also coated to increase lubricity, provide electrical insulation and to isolate from corrosive biofluids.
- ***Mandrels*** – An appropriate coating will reduce the coefficient of friction, act as a release agent, insure a particulate-free surface, eliminate microscopic flaking, smooth the mandrel surface and extend the useful life of the mandrel in production.
- ***Brain Probes*** – Benefit from the increased lubricity of a coating, and may require selective insulation to suit the conductive function of the part.
- ***Needles*** – An effective coating can seal microporosity, improve lubricity, cover both inside and outside needle surfaces, and add essentially nothing to the nominal dimensions of the device.

J-2.2 Long Term or Permanent Applications

- ***Electronic Circuits*** – The coating isolates from moisture and corrosive biological effects, and electrically insulates by a conformal coating.
- ***Cardiac Assist Devices*** – Are isolated from corrosive biofluids, and electrically insulated by a conformal coating.
- ***Pipette/Microplate Trays*** – The coating serves to seal microporosity, and isolates surfaces from corrosive biofluids, moisture and chemicals.

APPENDIX K
Example of Stringent Test for Any Breach in A Conformal Coating

K-1 The lack of integrity testing, realistic environmental test requirements, information about physical characteristics of coatings and knowledge about the synergistic chemical reactions which occur has made the determination of circuitry reliability in harsh environments impossible.

Testing the integrity of coatings is needed to assure that microscopic pinholes and voids would not allow moisture and contaminates to disrupt circuitry operation. Currently the only 'integrity test' is not a test but rather an inspection done under ultra-violet light. Most coatings are treated to fluoresce when exposed to UV light. This "black light" inspection process may not reveal microscopic pinholes, voids (even under magnification), and are incapable of determining the thickness of the coating.

There are several different approaches to solve these deficiencies. Using test coupons with dummy components, prototype units, or samples of production units placed in an environmental chamber it is possible to determine if there are production problems by creating condensation on the coated surfaces of the PCAs while bias is applied and measuring the leakage currents. This type of test will help verify application processes and material selection.

A faster, though not as comprehensive, test can be done by rolling a moist Q-Tip or swab over the circuitry while it is operating and observe any abnormal operation of the circuitry. Another test is called the "water drop test." In this case a drop of water is placed on a suspect area while observing the operation of the circuit for any abnormalities. When these tests are performed on production units care should be taken not to leave the moisture on the surface for more than a few seconds or contamination may result. Up to a 20 to 40% failure rate for newly coated boards using these moisture tests can be expected. These high failure rates will primarily involve liquid solvent type spray, dipped, or brushed on coatings. The water drop and Q-Tip tests can also be performed in the field to test for coating damage.[36]

36. Douthit, D.A., "Avionics Systems, Reliability, and Harsh Environments," May 2001.

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